2MASS wide field extinction maps: I. The Pipe nebula

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ABSTRACT

\textbf{Aims.} We present a 8° × 6°, high resolution extinction map of the Pipe nebula using 4.5 million stars from the Two Micron All Sky Survey (2MASS) point source catalog.

\textbf{Methods.} The use of Nicer (Lombardi & Alves 2001), a robust and optimal technique to map the dust column density, allows us to detect a $A_V = 0.5$ mag extinction at a 3-σ level with a 1 arcmin resolution.

\textbf{Results.} (i) We find for the Pipe nebula a normal reddening law, $E(J - H) = (1.85 \pm 0.15)E(H - K)$. (ii) We measure the cloud distance using Hipparcos and Tycho parallaxes, and obtain $130^{+28}_{-58}$ pc. This, together with the total estimated mass, $10^4 \, M_\odot$, makes the Pipe the closest massive cloud complex to Earth. (iii) We compare the Nicer extinction map to the NANTEN $^{12}$CO observations and derive with unprecedented accuracy the relationship between the near-infrared extinction and the $^{12}$CO column density and hence (indirectly) the $^{12}$CO X-factor, that we estimate to be $2.91 \times 10^{20} \, \text{cm}^{-2} \, \text{K}^{-1} \, \text{km}^{-1} \, \text{s}$ in the range $A_V \in [0.9, 5.4]$ mag. (iv) We identify approximately 1,500 OH/IR stars located within the Galactic bulge in the direction of the Pipe field. This represents a significant increase of the known numbers of such stars in the Galaxy.

\textbf{Conclusions.} Our analysis confirms the power and simplicity of the color excess technique to study molecular clouds. The comparison with the NANTEN $^{12}$CO data corroborates the insensitivity of CO observations to low column densities (up to approximately 2 mag in $A_V$), and shows also an irreducible uncertainty in the dust-CO correlation of about 1 mag of visual extinction.

\textbf{Key words.} ISM: clouds, dust, extinction, ISM: structure, ISM: individual objects: Pipe molecular complex, Methods: data analysis

1. Introduction

Nearby Galactic molecular clouds complexes represent our best chance to understand cloud formation and evolution and hence to learn how stars come to be. But progress on the study of these objects has been slow. Not only are molecular clouds the coldest objects known in the Universe, their main mass component ($\text{H}_2$) cannot be detected directly. Most of all we know today about their physical properties has been derived through radio spectroscopy of $\text{H}_2$ surrogate molecules (CO, CS, NH$_3$; e.g., Blitz & Williams 1999, Myers 1999) and more recently through thermal emission of the dust grains inside these clouds (Andre et al. 2000, Johnstone et al. 2000). The results obtained using these techniques, especially the estimate of column densities, are not always straightforward to interpret and are plagued by several poorly constrained effects. Moreover, although large scale maps of entire molecular cloud complexes are now available (Heyer et al. 1998, Simon et al. 2001), maps with sufficient resolution and dynamic range to identify not only dense molecular cores but also their extended environment are still not existent. This wide view on molecular clouds is at present an obvious gap in our understanding of the relation between the dense Interstellar Medium (ISM) and star formation.

A straightforward and powerful technique to study molecular cloud structures, pioneered by Lada et al. (1994) and known as the Near-Infrared Color Excess method (NICE, Alves et al. 1998) makes use of the most reliable tracer of $\text{H}_2$ in these clouds: extinction by pervasive dust grains in the gas. The NICE method relies on near-infrared (NIR) measurements of extinguished background starlight to derive accurate line-of-sight estimates of dust column densities. Depending on the stellar richness and color properties of the background field this technique can produce column density maps with spatial resolutions down to 5 arcsec (e.g., Alves et al. 2001, 2002) and with dynamic ranges more then an order of magni-
tude larger than classical optical star count techniques. This novel view on molecular clouds is providing not only new information on the physical structure of these objects (Alves et al. 2001) but also an insight into their chemical structure and the physical properties of the dust grains, when combined to molecular line and dust emission data (Kramer et al. 1999, 2001; Alves et al. 1999; Bergin et al. 2001; Lada et al. 2003; Bianchi et al. 2003; Kramer et al. 2003).

In part to make use of the wealth of NIR data provided by the Two Micron All Sky Survey (2MASS; Kleinmann et al. 1994), the NICE method was further developed into an optimized multi-band technique dubbed Near-Infrared Color Excess Revisited (Nicer, Lombardi & Alves 2001, hereafter Paper I). This generalization of NICE can, nevertheless, be applied to any multi-band survey of molecular clouds. Through use of optimal combinations of colors, Nicer improves the noise variance of a map by a factor of two when compared to Nice. This unique property of Nicer makes it the ideal tool to trace large scale distributions of low column density molecular cloud material. When applied to 2MASS data, Nicer dust extinction maps trace not only the low column density regions ($A_V \simeq 0.5$ mag) but have the dynamic range to identify dense molecular cores by reaching cloud depths of $\sim 30$ mag of extinction, corresponding to $8 \times 10^{22}$ protons cm$^{-2}$ (Lombardi 2005b).

In this paper we present an extinction map of the Pipe nebula covering 48 sq deg, computed by applying the Nicer technique on 4.5 millions JHK photometric measurements of stars from the 2MASS database. The Pipe nebula is a poorly studied nearby complex of molecular clouds. The only systematic analysis of this region is the one of Onishi et al. (1999) who present a $\sim 27$ sq deg map in the $J = 1 - 0$ line of $^{12}$CO observed on a 4 arcmin grid, and smaller maps of selected regions in the $J = 1 - 0$ lines of $^{13}$CO and $^{18}$O. They estimate the total $^{12}$CO mass to be $\sim 10^4$ M$_\odot$ (for a cloud distance of 160 pc) and point out that star formation is only occurring on Barnard 59, where the $^{18}$O column density is the highest and where they find a CO outflow. Barnard 59 was also observed at 1300 $\mu$m by Reipurth et al. (1996) and a protostellar candidate B59-MMS1 was found. Two pre-main sequence stars associated with Barnard 59 appear in the young binaries survey of Reipurth & Zinnecker (1993) and more recently in Koresko (2002).

This paper is organized as follows. In Sect. 2 we describe the technique used to map the dust in the Pipe nebula and we present the main results obtained. In Sect. 3 we address the determination of the cloud distance using Hipparcos data. A statistical analysis and a discussion of the bias introduced by foreground stars is presented in Sect. 4. We compare the CO observations from Onishi et al. (1999) with our outcome in Sect. 5. Section 6 is devoted to the mass estimate of the cloud complex. Finally, we summarize the conclusions of this paper in Sect. 7.

Fig. 1. Color optical image of the region around the Pipe nebula. The bright “star” on the top-right is Jupiter; below it are well visible the $\rho$-Ophiuci dark cloud and the Lupus complex. The white box encloses the field studied in this paper. The Pipe nebula obscures part of the Galactic bulge, and thus occupies an exceptional location for infrared studies (image courtesy Jerry Lodriguss, http://www.astropix.com/).

In the following we will normally express column densities in terms of the 2MASS $K_s$ band extinction $A_K$. When converting this quantity into the widely used visual extinction $A_V$, we will use the Rieke & Lebofsky (1985) reddening law converted into the 2MASS photometric system (see Carpenter 2001), $A_K/A_V = 0.112$.

2. Nicer extinction map

The data analysis was carried out using the Nicer method described in Paper I (to which we refer for more detailed information). Infrared $J$ (1.25 $\mu$m), $H$ (1.65 $\mu$m), and $K_s$ (2.17 $\mu$m) magnitudes of stars in the Pipe region were obtained from the Two Micron All Sky Survey$^1$ (2MASS; Kleinmann et al. 1994). We selected a large region around the Pipe nebula, characterized by galactic coordinates

$$-4^\circ < l < +4^\circ , \quad +2^\circ < b < +8^\circ .$$

As shown by these coordinate ranges, the Pipe nebula occupies an exceptionally good location for infrared studies. Indeed, this cloud complex is just above the galactic plane and is in front of the galactic bulge (see Fig. 1). The cloud, we anticipate, is approximately at 130 pc (see Sect. 4), and thus almost all the stars observed in direction of the cloud are background objects. As a result, we could carry out the study of the infrared extinction of the cloud with negligible contamination by foreground objects (except in the most dense regions).

The high density of stars in the Pipe region has also some drawbacks. Indeed, because of confusion, the nominal 2MASS photometric completeness limits drop close

\footnote{See http://www.ipac.caltech.edu/2mass/}
Fig. 2. Color-color diagram of the stars in the Pipe nebula field, as a density plot. The contours are logarithmically spaced, i.e. each contours represents a density ten times larger than the enclosing contour; the outer contour detects single stars and clearly shows a bifurcation at large color-excesses.

to the galactic center. In the case of NicER (in contrast with the star-counting method), this does not affect the measurements of column densities because no assumptions are made about the local star density. High density regions also pose severe challenges for data reduction. For example, the pipeline used for the Second Incremental Release of 2MASS produced slightly inaccurate zero-points. This problem showed on the NicER maps of the Pipe nebula as abrupt artificial changes in the measured column density at the boundaries of the 2MASS observation tiles. Fortunately, the pipeline has been greatly improved and this problem does not appear in the final 2MASS All Sky Release.

After selecting point sources from the 2MASS catalog inside the boundaries (1), we generated a preliminary extinction map. As described in Paper I, this map was mainly used as a first check of the data, to select a control region on the field, and to obtain there the photometric parameters to be used in the final map (see Fig. 7). We note that the search of a control field close to the Pipe nebula has been non-trivial, because of the complex cloud structure and high column densities observed at low galactic latitudes. We identified in the Eastern part of our field (top-right in Fig. 7) a small region that is apparently affected by only a negligible extinction (see below); note that the newly determined Indebetouw et al. (2005) 2MASS reddening law was used at this stage.

Using the information provided by the control field, we generated a second map, which is thus “calibrated” (i.e., provides already, for each position in our field, a reliable estimate of the column density). We then considered the color-color diagram for the stars in the catalog. The result, shown in Fig. 2, shows a surprising bifurcation for \( H - K > 1 \) mag, which in principle might represents a problem in color-excess studies.

In order to further investigate the origin of this bifurcation, we considered the region \( H - K > 1 \) mag in the color-color diagram, and divided it into two subsamples \( A \) (upper branch) and \( B \) (lower branch) according to the expressions

\[
A \equiv \{ 1.4(H - K) + 0.5 \text{ mag} < (J - H) \} ,
\]

\[
B \equiv \{ 1.4(H - K) + 0.5 \text{ mag} > (J - H) \} .
\]

We then analysed the spatial distribution of the stars contained in the two regions. The results, shown in Fig. 3, give a first strong indication that, as expected from their location in the color-color diagram, subsample \( A \) is associated with the densest regions of the molecular cloud and thus it has to be interpreted as normal stars reddened by the dust, while subsample \( B \) does not appear to be associated with the cloud. Interestingly, subsample \( B \) is uniformly distributed in galactic longitude, but has a strong preference for low galactic latitude regions.

Further hints on the nature of the two stellar populations in subsamples \( A \) and \( B \) are given by the histogram of their \( K \) band magnitudes, shown in Fig. 4. Interestingly, while subsample \( A \) stars show, as expected, a broad distribution, with number counts increasing at relatively large
Fig. 5. The extinction-corrected color-color diagram for the Pipe nebula. The stripes show both subsamples $B_1$ and $B_2$ of Eqs. (2) and (3).

These stars are unrelated to the molecular cloud reddening and appear to be located close to the galactic plane. A deeper analysis, carried out on a much larger field (Lombardi et al., in prep.), actually shows that the stars are preferentially located on the galactic bulge.

The stars occupy a well-defined region in the (extinction-corrected) color-color diagram. This indicates that the “lower branch” represents a well-defined population of stars.

The $K$ band distribution of “lower branch” stars is strongly peaked at $K \simeq 7$ mag. This not only is a further indication that we are looking at a homogeneous population, but also suggests that these stars are at essentially the same distance. The $K$-band standard deviation is approximately 0.8 mag (if the tail at $K > 10$ mag of Fig. 4 is neglected), and since this must account for the scatter in the absolute magnitude, the scatter in the distance, and the photometric errors, it is likely that these stars have a relative scatter in their distance of the order of 25% or less. Again, this is a further hint that the “lower branch” stars might be a bulge population.

The distribution of “lower branch” stars in the color-color diagram (Fig. 2) forms an elongated region parallel to the reddening vector. This shows that at least part of the large scatter in their intrinsic colors might be due to reddening, local or along the line of sight.

The items above suggest that the “lower branch” might be populated by evolved intermediate mass stars (about 1 to 7 $M_\odot$), and likely on the Asymptotic Giant Branch (AGB), at about the distance to the Galactic center. We find a similarity between the “lower branch” stars and the sample of Galactic OH/IR stars in Jiménez-Esteban et al.

Fig. 4. The histogram of the $K$ band magnitude for the two star subsets $A$ and $B$ of Eqs. (2) and (3).
These authors conclude that the luminosity and color distribution observed could be explained as the result of a combined emission of a cool star ($T \sim 2500$ K) and a much cooler dust shell ($T < 800$ K). The main effect of the shell in the near-infrared colors would be to increase the circumstellar reddening, which, together with differential interstellar extinction effects from source to source, could explain the width of the distribution observed. Although we will not explore further in this paper the nature of these stars, we note that they are particularly interesting objects, and given the large number of identifications in our fields (we have approximately 45 000 $B_1$ stars and 1 500 $B_2$ ones) a dedicated study is warranted.

The “lower branch” stars seem to be unrelated to the molecular cloud, but their colors would be interpreted by the NICER algorithm as a sign of extinction. This, clearly, could in principle bias our results toward a higher extinction, especially at low galactic latitude regions. However, we argue that the bias introduced by “lower branch” stars is negligible. Indeed, the density of these objects is, in the worse case (set $B_1$) only 1% of the average density of stars, so that typically we have at most one “lower branch” star contaminating each pixel, and since we have $\sim 30$ stars per pixels, the effects of “lower branch” stars is negligible everywhere.

Nevertheless, and in order to avoid any source of bias, although small, we excluded from the 2MASS catalogs all stars located in the $B_2$ color-space region, and performed the whole analysis described in this paper using this reduced subset of stars. We stress that if we had performed a cut in the observed colors, we would be have introduced a new bias in the deduced column density; instead, the use of a select in the intrinsic colors does not bias the final results. As an example, Fig. 6 shows the color-color diagram for the new set of stars; note that the “lower branch” disappears completely in this plot, a further confirmation that our selection is effective in removing this population of stars.

We then run again the whole NICER pipeline on the refined catalog. After re-evaluating the statistical properties of stars in the control field, we constructed the final map, shown in Fig. 7, in a grid of approximately $1 \times 750$ points, with scale 30 arcsec per pixels, and with Gaussian smoothing characterized by FWHM $= 1$ arcmin; moreover, we used an iterative $\sigma$-clipping at 3-$\sigma$ error. The final, effective density of stars is $\sim 8$ stars per pixel (this value changes significantly on the field with the galactic latitude, see Fig. 8); this guarantees an average (1-$\sigma$) error on $A_K$ of only 0.019 magnitudes; the largest extinction is measured close to Barnard 59, where $A_K \simeq 2.68$ mag (corresponding to approximately $A_V \simeq 24$ mag). As clearly shown by Fig. 8, the combination of the use of the 2MASS archive with the optimized NICER technique allows us to reveal an unprecedented number of details. A quantitative analysis of this extinction map is delayed until Sect. 4.

Figure 9 shows the expected error $\sigma_{A_K}$ versus the measured extinction $A_K$ for the various pixels in the extinction map of Fig. 7, shown as a density plot.
Fig. 7. The NicER extinction map of the Pipe nebula. The resolution is FWHM = 1 arcmin; the contours are at $A_K = \{0.5, 1, 1.5\}$ mags.

3. Distance

An accurate determination of the distance of molecular clouds is of vital importance to obtain a reliable estimate of the mass and of other physical properties. Unfortunately, distance measurements of molecular clouds are frequently plagued by very large uncertainties. A simple method used often is based on the association between the cloud and other astronomical objects whose distance is well known. Onishi et al. (1999) associate the Pipe nebula with the Ophiuchus complex on the base of projected proximity and radial velocity and use the distance of the latter, $(160 \pm 20)$ pc, as the distance to the Pipe (Chini 1981).

An alternative approach is based on the number counts of foreground stars. The method, used for example in Alves et al. (1998), exploits the large reddening produced by some clouds, which makes the identification of foreground stars relatively easy; then, galactic models (e.g., Bahcall & Soneira 1980, Wainscoat et al. 1992) are used to infer the expected number of stars (for each possible cloud distance) inside the cone created by the cloud. Finally, the number of foreground stars observed is compared to the prediction and the distance of the cloud is inferred. Although this method is often the best one can use, it is unable to give accurate distances for several reasons: (i) it relies on galactic models, which might be inaccurate (especially at the small angular scales often used...
Fig. 8. The star density map for the extinction map of Fig. 7, i.e. the number of stars inside a (Gaussian) 1 arcmin beam. The dark structures correspond mostly to the position of dense cores in the Pipe nebula where the star density is minimal due to high extinction. The black “holes” outside the Pipe body correspond to masked bright stars while the white spots correspond to globular clusters.

We selected Hipparcos and Tycho-1 (I/239) stars observed in the area defined in Eq. 11, and matched these stars with the “All-sky Compiled Catalog of 2.5 million stars” (ASCC-2.5, I/280A; Kharchenko 2001) and with the “Tycho-2 Spectra Type Catalog” (Tycho-2spec, III/231; Wright et al. 2003). The choice of these two latter datasets (which are cross-references and merges of many stellar catalogs) was dictated by the need to obtain for each star with measured parallax an estimate of its spectral type. In particular, the use of ASCC-2.5 and of Tycho-2spec effectively allowed us to cover a large sample of spectroscopic catalogs: the Hipparcos catalog (I/239), the Carlsberg Meridian Catalogs (CMC11; I/256), the Position and Proper Motions (PPM: I/146, I/193, I/208), the Michigan Catalogs (III/31, III/51, III/80, III/133, III/214), the Catalog of Stellar Spectra Classified in the Morgan-Keenan System (III/18), the MK Classification Extension (III/78), and the FK5 catalog parts I and II (I/149 and I/175).

We considered all stars in our field with measured parallax larger than the parallax error, and with spectral type
Fig. 9. The map shows the statistical error $\sigma_{A_K}$ on the measured column density. Note that correlation on the errors on a scale of FWHM = 1 arcmin is expected. This map shows that for almost the whole field $A_K = 0.05$ represents a 3-$\sigma$ detection.

B, A, F, G, K, or M. By comparing the expected $B - V$ color (taken from Landolt-Börnstein [1982, p. 15]) with the observed one, we obtained an estimated of the color excess $E(B - V)$; we finally converted this into an extinction in the $V$ band $A_V$ by using a normal reddening law, $A_V = 3.09 E(B - V)$ (Rieke & Lebofsky [1985]). Note that, whenever possible, we used 2D spectral types; for 1D spectral types we assumed a luminosity class IV.

A plot of the star column density versus the Hipparcos and Tycho2 parallaxes is shown in Fig. [11]. Because of the relative large scatters in the parallax and column density measurements, Fig. [11] is not straightforward to interpret. However, we note the following points.

1. At large parallaxes, for $\pi > 12$ mas, the measured extinction is low and consistent, within the errors, with a constant value. The average extinction in this range, $\langle A_V \rangle = 0.12$ mag, either suggests the presence of a thin “veil” very close to us or of a small systematic error in the estimate of $A_V$. The presence of absorbing material towards the location of the Pipe nebula at distances below 50 pc is also suggested by the recent work of Lallement et al. [2003], where they construct 3D absorption maps of the local distribution of neutral gas through measurements of equivalent widths of the interstellar NaI D-line doublet towards nearby stars. In any case, from Fig. [11] we can deduce a robust lower limit on the cloud distance, $d > 80$ pc. Note that, interestingly, we also detect a near single star (HD 158233) at $(55.0 \pm 1.67)$ mas with significant reddening, $A_V = (0.38 \pm 0.06)$ mag; thus, if the reddening has to be attributed to a thin molecular cloud, its distance would be smaller than 20 pc.

2. As we go to smaller parallaxes we start seeing stars with signs of a possible reddening. A first candidate is a star at 90 pc with $A_V = (1.11 \pm 0.66)$ mag (well visible in Fig. [11]; however, the large error on $A_V$ does not allow us to assess securely that the star has been significantly reddened by the cloud.

3. At approximately $\pi = 7.3$ mas ($\sim 137$ pc) we observe four stars with relatively large extinction, $A_V > 0.9$ mag, and with relative small errors (the ratio $A_V/Err(A_V)$ ranges from 4.3 to 27.5). Hence, these stars give an upper limit to the cloud distance, $d < 140$ pc.
that we can take the star column density as a random variable whose distribution only depends on the intrinsic measurement errors and on the parallax of the star. The simplest sensible approach is to consider a bimodal distribution for each star column density, where the extinction of stars in front of the nebula is consistent (within the measurement errors) with zero, and the extinction of stars at distances larger than the cloud can be either still zero (if the star is not observed through the cloud) or finite and with a large scatter (if the star is behind the cloud). In this case, the conditional probability of observing a star with visual extinction $A_V$, given the fact that the star is located at a parallax $\pi$ is

$$p(A_V | \pi) = \begin{cases} 
Gau(A_V | A_V^{\pipe}, \sigma_{A_V}^{\pipe}) + fGau(A_V | A_V^{fg}, \sigma_{A_V}^{fg}) & \text{if } \pi > \pi_{\pipe} \\
(1 - f)Gau(A_V | A_V^{\pipe}, \sigma_{A_V}^{\pipe}) + fGau(A_V | A_V^{fg}, \sigma_{A_V}^{fg}) & \text{if } \pi \leq \pi_{\pipe} 
\end{cases}$$

where we denoted with $Gau(x | \mu, \sigma_x)$ the value at $x$ of a normal probability density with mean $\mu$ and variance $\sigma_x^2$ [cf. Eq. (12)]. In other words, we use a normal distribution with low average $A_V^{\pipe}$ for foreground stars, and the mixture of the same distribution with another normal (with large average $A_V^{fg}$) for background stars. For both distributions the variance was set to the sum of $\sigma_{A_V}^{\pipe}$, the estimated variance in the measured column density of the star, and $\sigma_{A_V}^{fg}$ (respectively, $\sigma_{A_V}^{bg}$), the intrinsic variance of the foreground (background) distributions. The parameter $f \in [0,1]$ used in Eq. (6) represents the filling factor, i.e. the ratio between the area of the sky occupied by the cloud and the area of the whole field.

We considered this simple model leaving as free parameters $\{\pi_{\pipe}, f, A_V^{fg}, \sigma_{A_V}^{fg}\}$ (the average foreground $A_V$ and its variance were deduced from the stars with measured parallax $\hat{\pi} > 12$ mas). In order to assess the goodness of a model, we computed the likelihood function, defined as

$$\mathcal{L} = \prod_{n=1}^{N} \int_0^{\infty} p(A_V^{(n)} | \pi) p(\pi | \hat{\pi}^{(n)}) \, d\pi ,$$

where the product is carried over all $N$ observed stars with parallax, and where $p(\pi | \hat{\pi}^{(n)})$ is the probability distribution that the $n$-th star with measured parallax $\hat{\pi}^{(n)}$ has a true parallax $\pi$. The integral in Eq. (7) takes into account the possibility that a star with a measured parallax $\hat{\pi} < \pi_{\pipe}$ (or $\hat{\pi} > \pi_{\pipe}$) is incorrectly taken as background (respectively, foreground) because of its large parallax error $\hat{\sigma}_\pi$. In our analysis, we used for $p(\pi | \hat{\pi}^{(n)})$ a simple normal distribution with standard deviation equal to the formal error on the measured parallax $\hat{\sigma}_\pi^{(n)}$:

$$p(\pi | \pi^{(n)}) = \text{Gau}(\pi | \pi^{(n)}, \hat{\sigma}_\pi^{(n)2}) .$$

We note that this particular choice allows us to evaluate the integrals of Eq. (7) analytically in terms of the error function erf.

In order to study in detail the likelihood function in its multidimensional parameter space we used Monte Carlo.
Carlo Markov Chains (MCMC; see, e.g. [1991]). The obtained results are summarized by Fig. [12] where we show the marginalized likelihood as a function of the cloud parallax \( \pi \). As best estimate for the cloud distance we take the median of the distribution shown in Fig. [12] \( d_{\text{pipe}} = 130 \) pc; the formal 68\% (respectively, 95\%) confidence regions are \([110, 143]\) pc and \([72, 154]\) pc. Note that the best fit value obtained for the filling factor is \( f = 0.42 \), which compares well with the value directly measured in the map of Fig. [4] (41\% of the area in our field has a measured extinction \( A_V > 3 \) mag).

In summary, in the rest of this paper we will use a estimate of the cloud distance \( 130^{+13}_{-20} \) pc. The formal error is relatively small, but it is probably underestimated (e.g., the error due to a possible misclassification of the spectral type of a star was not included in the error budget); moreover, because of the relatively small number of reddened stars, the distance obtained appears to be slightly model-dependent. Our distance estimate is likely to be biased towards large values because the method used gives an upper limit (this is also suggested by the long tail at large parallaxes in the likelihood function of Fig. [12]). With the advent of the new generation astrometric missions such as Gaia [1990] it will be possible with this or similar methods to accurately measure the distances of a large sample of molecular cloud complexes.

4. Statistical analysis

4.1. Star extinction

In Fig. [13] we plot the distributions of column densities obtained for stars observed in low-extinction (\( -0.05 < A_K < 0.05 \) on the extinction map); the dashed line the same distribution for stars in high-extinction regions (\( 1.15 < A_K < 1.25 \)).

![Fig. 13. The distribution of individual star extinctions. The solid histogram shows the distribution of column densities for stars observed in low-extinction regions (\(-0.05 < A_K < 0.05\) on the extinction map); the dashed line the same distribution for stars in high-extinction regions (\(1.15 < A_K < 1.25\)).](image)

In Fig. [14] we plot the distributions of column densities for stars observed in low-extinction (\( -0.05 < A_K < 0.05 \)) and high-extinction regions (\( 1.15 < A_K < 1.25 \)). The two histograms show two similar Gaussian shapes, but the one corresponding to high-extinction has a larger width (the best-fit Gaussian dispersions are \( \sigma_1 = 0.210 \) mag and \( \sigma_2 = 0.272 \) mag). This increase can be due to a number of factors: (i) the increase of photometric errors for the faint stars observed through dense clouds, and the lack of the \( K \) band photometry for most of these objects; (ii) the internal structure of the cloud on scales smaller than our resolution (which, we recall, is FWHM = 1 arcmin); (iii) an increase in the contamination of foreground stars (see below Sect. [14]).

Among these factors, (i) can be evaluated from the photometric errors of the 2MASS database, and appears to negligible (i.e., there is no significant increase in the photometric error of stars in moderately extincted regions, cf. Fig. [10]). On the other hand, factors (ii) and (iii) are difficult to disentangle, because they essentially produce the same effects (see below).

The increase of the dispersion on \( A_K \) at large column densities can be evaluated more quantitatively from Fig. [14]. This figure has been obtained from the map of the dispersion of \( A_K \) (not shown here). This map is constructed by evaluating, for each pixel of Fig. [4] the scatter of the column density estimates corresponding to each star. Hence, large values in some pixels of this map mean that the stars used to estimate \( A_K \) in the corresponding pixels of Fig. [4] present very different reddening values (see Paper I for the analytic definition of the scatter map). Figure [14] has been obtained by plotting the average values observed in the dispersion map in pixels characterized by a given value of \( A_K \) in Fig. [4]. We note that the observed increase in the dispersion of \( A_K \) has been...
obtained in several similar studies (e.g., Lada et al. 1994, Alves et al. 1998, Lada et al. 1999).

As we mentioned above, in our case it is difficult to attribute the effect observed in Fig. 14 with certainty to foreground stars or to substructures. Consider, as an example, a “two-dimensional Swiss cheese” molecular cloud, i.e., a thin cloud with many holes (some of them smaller than the resolution of our maps). In this case, a background star observed through a small hole will produce exactly the same statistics as a foreground star. Hence, in this case it will be impossible to distinguish foreground stars and substructure. In less extreme (and more physical) situations it is generally possible to firmly identify, in the dense regions of the cloud complexes, foreground stars. However, this task is unfortunately non-trivial for the Pipe, because of its filamentary structure and of the relatively low resolution attainable with the 2MASS data. Still, our estimate indicates that only an extremely small fraction $F_0 \approx 0.003$ of foreground stars is present in our map (see below Sect. 4.4), and thus they have a negligible contribution to the effect observed in Fig. 14 (cf. dashed line in that figure). In summary, we attribute most of the increase in the dispersion of $A_K$ to unresolved substructures. A further indication of this is given by similar analyses of molecular clouds carried out at a higher resolution (e.g., Lada et al. 2004), which show a dispersion $\sigma_{A_K}$ substantially independent of $A_K$ (i.e., a flat curve in the $A_K-\sigma_{A_K}$ plot). In a follow-up paper (Lombardi 2005b) we will further investigate the effect of substructures in molecular clouds.

4.2. Reddening law

The reddening law plays a fundamental role in any infrared dust measurement since it is used to derive the column dust density from the properties of background stars. In particular, a key assumption is that the reddening law is linear, i.e., that the ratio $A_{\lambda_1}/A_{\lambda_2}$ of extinctions in two different wavelengths is constant. Since the intrinsic luminosities of stars are not known, we cannot measure directly the extinction $A_{\lambda}$ in a single band; in the NIR, however, we can measure with good accuracy the color excess $E(m_{\lambda_1}-m_{\lambda_2}) = A_{\lambda_1}-A_{\lambda_2}$, and this is the essence of the NICE and NICER techniques. Moreover, if we have good photometry in three bands, say $J$, $H$, and $K$, we can indirectly verify the assumption of a linear reddening law by checking that the color excesses $E(H-K)$ and $E(J-H)$ are linearly dependent. The large number of stars in the field allows us to perform this check with great accuracy.

The linearity of the reddening law, ultimately, is equivalent to say that the stars in the color-color plot are mostly the same statistics as a foreground star. Hence, in this part, might be the origin of some discrepancies found in the literature about the slope of the reddening law (another good reason are the different NIR photometric systems used by different authors).

For example, in order to measure the slope of the reddening law, we can fit all star colors (or color excesses) with a linear relation:

$$(J-H) = \alpha(H-K) + \beta,$$

where $\alpha = (A_J-A_H)/(A_H-A_K)$ and $\beta$ are taken to be constant for all stars. Naively, the fit could be done directly on the individual star colors $\{H_n-K_n\}$ and $\{J_n-H_n\}$, by minimizing the expression

$$\chi^2 = \sum_{n=1}^{N} \left[ \alpha(H_n-K_n) + \beta - (J_n-H_n) \right]^2,$$

or similar expressions taking into account the photometric errors of stars. In reality, such a procedure leads to unsatisfactory results because the large majority of stars are subject to small or negligible reddening. In other words, a minimization of Eq. 10 would basically take into account only the lower-left part of the plot of Fig. 6b and would neglect the most interesting (highly reddened) stars (say, $H-K > 1$ mag).

In order to equally take into account all reddening regimes, we followed here a different procedure:

1. We evaluated the column density of each star by using the normal reddening law considered in this paper (Indebetouw et al. 2005).
2. We binned the stars according to their extinction in bins of 0.02 mag.

![Fig. 15. The reddening law as measured on the analyzed region. The plot shows the color excess on $J-K$ as a function of the color excess on $H-K$ (the intrinsic colors, deduced from the control field, are 0.18 and 0.60 respectively); the solid line shows the best fit. Error bars represent the standard deviation of color excesses inside the bin.](image-url)
3. In each bin, we evaluated the average color excesses in \( H - K \) and \( J - H \), and the standard deviation in \( J - H \). Note that the standard deviation in \( J - H \) was calculated by referring all star colors inside the bin to the average \( H - K \) color, or equivalently by evaluating the standard deviation of the expression

\[
E(J - H)_{\text{corr}} = -\alpha \left[ E(H - K) - \langle E(H - K) \rangle \right] + E(J - H) .
\]

This procedure ensures that the scatter in \( E(J - H)_{\text{corr}} \) does not include the scatter due to the finite size of the bin in \( K - H \).

4. We fitted all positive bins with a linear relationship of the form of Eq. (9) (in the fit we took into account the standard deviations evaluated in the previous point).

5. Finally, we repeated the whole procedure using the newly determined reddening law until convergence is achieved (which typically happens after two or three iterations).

The method presented above has many pleasant properties. First, all reddening regimes equally contribute to the fit, since by construction we equally use all bins of different column densities. This, in turn, implies that the method is robust against bright stellar populations that might artificially change the slope of the reddening law (cf. above Sect. 2). Moreover, the use of the observed standard deviations on the \( J - H \) color for the fit properly takes into account local deviations from a reddening law or increased photometric errors for reddened stars.

We applied the method described above to our data, by selecting all 2MASS stars with accurate photometry in all bands (we required all photometric errors to be smaller than 0.1 mag) from the cleaned catalog (cf. above Sect. 2); the results obtained are summarized in Fig. 13. We found as best fit slope \( \alpha = 1.82 \pm 0.03 \), a value that appears to be in excellent agreement both the Indebetouw et al. (2005) 2MASS reddening law, \( E(J - K)/E(H - K) = 1.78 \pm 0.15 \), and with the Rieke & Lebofsky (1985) \( E(J - K)/E(H - K) = 1.70 \) normal reddening law converted into the 2MASS internal photometric system \( \text{Carpenter 2001} \), which is \( E(J - K)_{\text{2MASS}}/E(H - K)_{\text{2MASS}} \approx 1.89 \).

In follow-up papers we will apply the same technique to other cloud complexes studied from the 2MASS archive. The uniformity of the 2MASS data and of the procedure used to deredden the reddening law will allow us to accurately study cloud-to-cloud variations (see, e.g., Kenyon et al. (1998) for a case where significant differences from a standard reddening law are found).

4.3. Smoothing method

As discussed in Paper I, the pipeline developed allows us to obtain smooth maps of the discrete column density measurements (obtained for each background star) in three different ways: simple average, sigma-clipping, and median map. For the simple average we use all column density measurements close to each pixel, and the extinction value assigned to the pixel is a weighted average of the \( A_K \) measurements for each star. The weight takes into account both the statistical error on \( A_K \) (which is due to the photometric errors and to the intrinsic scatter of star colors), and the angular distance between the star and the pixel. For the sigma-clipping, instead, we selectively discard outliers on \( A_K \), i.e. stars that have associated col-
This figure compares the column densities obtained through sigma-clipping and simple average, similarly to what done in Fig. 17 for the median.

Fig. 18. This figure compares the column densities obtained through sigma-clipping and simple average, similarly to what done in Fig. 17 for the median.

In conclusion, our analysis shows that the simple mean estimator, which has the smallest scatter, is reliable up to approximately $A_K \approx 1.5$ mag; for larger column densities, the median should be used in order to minimize the effect of foreground stars.

4.4. Foreground star contamination

The three smoothing methods described above differ significantly on the effect of foreground contamination. If we assume that a fraction $F > 0$ of stars are foreground with respect to the cloud, then the simple average estimate will be biased toward small column densities. In particular, the average measurement of $A_K$ will be $\langle A_K \rangle = (1 - F)A_K^{\text{true}}$. In contrast, the median will provide an (almost) unbiased estimate of $A_K$ as long as $F < 0.5$ (see Cambrésy et al. 2002 and Lombardi 2005a for a detailed discussion of the median properties). The sigma-clipping estimate will often be between these two extremes: it will be effective in removing foreground stars only in relatively dense regions and only for small values of $F$. Because of selection effects, the value of $F$ changes significantly on the field, and in particular increases in high-column density regions. This, in turn, implies that the correction to be used on the estimated value of $A_K$ is not constant on the field. In the case of the Pipe nebula only a few magnitude extinction in $V$ is observed in most of the field (see above Sect. 2, see also Fig. 27 below), and thus the value of $F$ is expected to be approximately constant. Moreover, since this cloud complex is very close to us and is observed close to the galactic center, we expect only a tiny fraction of foreground stars.
In order to evaluate quantitatively the density of foreground stars, we have selected high-extinction regions characterized by $A_K > 0.8$ mag and with relatively small expected error in $A_K$ (we allowed for a maximum error of 0.2 mag). In order to avoid the effects of possible substructures and ambiguities in the identification of foreground stars, we restricted our analysis to the main core of the Pipe nebula, i.e. to the region at $l \simeq 1.5^\circ$ and $b \simeq 4^\circ$ (see Fig. 7). We have then checked all stars in these regions that show “anomalous” extinction, i.e. stars whose column densities differ by more than 3-$\sigma$ with respect to the field. A total of 70 stars met this criteria; hence, since the area selected is approximately 1057 arcmin$^2$, we estimated a foreground star density of 0.066 arcmin$^{-2}$. As a result, the relative fraction of foreground stars in regions with negligible absorption is only $F|_{A_V=0} \equiv F_0 = 0.003$, and we can safely ignore the effect of foreground stars except on the higher extinction regions. Note, in particular, that a clear sign of very high extinction (very few background stars) and contamination by foreground stars is observed only in Barnard 59, where we see a “hole” in the extinction close to the center of this clump (see Fig. 14). In this case, these foreground stars are not really foreground but young stars moderately embedded in Barnard 59, an active star forming region (e.g. Onishi et al. 1999). Our estimate of $F_0$ allows us to evaluate the maximum theoretical extinction measurable with the NICE and NICER method: using Eq. (53) of Lombardi (2005a), we obtain $A_K^{\text{max}} \simeq 2.9$ mag, which is close to the maximum value measured here.

4.5. Column density distribution

A fundamental statistical property of a cloud is the distribution of column densities. Vázquez-Semadeni (1994) showed that for highly supersonic flows (such that the Mach number $M = u/c_s \gg 1$), the gas essentially has a pressureless behavior, and gravitational forces can also become negligible. In these conditions, the hydrodynamic equations become scale-invariant: in other words, motions at different length and density scales obey essentially the same equations. For a fully developed turbulent gas, density and velocity can be regarded as random fields. Because of the scale invariance, the probability of having a local (volume) density fluctuation of amplitude $\Delta \rho$ depends uniquely on the ratio $\Delta \rho/\rho$, i.e. on the relative fluctuation amplitude; hence, the probability distribution function of the density at each point of the cloud is expected to be lognormal. When projecting the three-dimensional mass density along the line of sight, the lognormal distribution is essentially preserved, i.e. the projected two-dimensional density is also expected to be well approximated by a lognormal distribution.

More recently, Vázquez-Semadeni (1994) argument has been investigated in more detail using various simulations by a number of authors (e.g. Padoan et al. 1997; Blum & Passot & Vázquez-Semadeni 1998; Klessen 2000), and in all cases the lognormal distribution was found to be a good approximation of the (projected) cloud density. However, Scalo et al. (1998) found that, contrary to previous claims, the density probability distribution is well approximated in their simulations by an exponential law in a relatively large range of physical parameters. Recently, this argument has been challenged by Ostriker et al. (2001) by showing a good agreement with a lognormal distribution in the molecular cloud IC5146 (Lada et al. 1999).

A direct study of the extinction distribution on a real cloud is a stringent test for simulations and ultimately also provides important hints on the physical conditions inside molecular clouds. We evaluated the column density distribution in the Pipe nebula by constructing the histogram of extinction measurements in each pixels of the map shown in Fig. 20 with $b > 3^\circ$, binned on suitable intervals (we used here 0.002 mag in $A_K$). The obtained distribution, plotted in Fig. 20, shows a complex shape with multiple peaks.

In order to compare the empirical distribution with a theoretical one, we used Poisson models for the individual columns. The best-fit parameters obtained from a fit of the column density distribution shown in Fig. 20 using a single lognormal distribution, three lognormal distributions, or four normal distributions.

| Distr.  | $x_0$ (mag) | $x_1$ (mag) | $\sigma$ (mag) | rel. factor |
|---------|-------------|-------------|----------------|-------------|
| lnGau #1 | $-0.241$ | $0.503$ | $0.325$ | $1.000$ |
| lnGau #2 | $-0.150$ | $0.413$ | $0.501$ | $0.150$ |
| lnGau #3 | $-1.805$ | $1.943$ | $0.018$ | $0.744$ |
| lnGau #4 | $0.039$ | $0.267$ | $0.371$ | $0.106$ |
| Gau #1  | $0.015$ | $-$ | $0.022$ | $0.086$ |
| Gau #2  | $0.123$ | $-$ | $0.033$ | $0.353$ |
| Gau #3  | $0.267$ | $-$ | $0.064$ | $0.395$ |
| Gau #4  | $0.419$ | $-$ | $0.118$ | $0.166$ |

Table 1. The best-fit parameters obtained from a fit of the column density distribution shown in Fig. 20 using a single lognormal distribution, three lognormal distributions, or four normal distributions.
ual histogram bins, and evaluated the joint probability to have the observed histogram in the range \(-0.3 \text{ mag} < A_V < 2 \text{ mag}\) (we excluded high \(A_K\) bins in order to avoid the complications inherent with large-column density regions). We constructed the theoretical models as sum of normal distributions

\[
Gau(x|x_0, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right),
\]

and lognormal ones

\[
\ln\text{Gau}(x|x_0, x_1, \sigma) = \frac{1}{(x-x_0)\sqrt{2\pi\sigma^2}} \exp\left(-\frac{[\ln(x-x_0) - \ln x_1]^2}{2\sigma^2}\right).
\]

As shown by Fig. 20, the best fit obtained from a single lognormal (dashed line) is surprisingly good given the complexity of the distribution; clearly, however, in this case we are only able to reproduce the general shape of the histogram and we are unable to generate finer details clearly visible in Fig. 20. As a measure of the quality of the fit, we note that the residuals are more than 150\(\sigma\) away from the observed histogram.

In order to improve the fit we added more components. However, two-component distributions still gave unsatisfactory results, and we had to use more components distributions to obtain a close match to the data. In particular, we verified that both the sum of four normal and three lognormal distributions gave similar fits, with residuals of the order of 8\(\sigma\). Hence although, in principle, the fit is still statistically inconsistent with the data, we note that in practice the large number of bins and the non-trivial structure of the Pipe nebula make it difficult to obtain good fits with a relatively small number of parameters. Note also that the need for several components in the column-density distribution is reminiscent of the velocity structures observed in the Pipe nebula from CO data (Onishi et al. 1999). In this respect, it is also likely that some of the “weak” components (e.g., the \(\ln\text{Gau} \#3\) or the Gau \#4) are related to background clouds observed in projection to the Pipe nebula at low galactic latitudes.

5. Comparison with CO analysis

Radio observations of \(H_2\) surrogates, and in particular of CO isotopes, provide an alternative independent estimate of the cloud gas column density. Onishi et al. (1999) studied in detail the Pipe nebula with the NANTEN radiotelescope and kindly provided their 12CO map to perform a comparison with the NICER analysis described in this paper. To this purpose, we constructed an extinction map using the same resolution (4 arcmin) and coordinate system of the NANTEN observations. In order to avoid any contamination by low-galactic latitude clouds, we excluded all measurements at \(b < 3^\circ\) (see Fig. 21).

Figure 22 shows the relationship between the NICER column density and the NANTEN integrated 12CO temperature, \(I_{12CO} \equiv \int T d\nu\). The large number of independent measurements shown in this figure (\(\sim 5000\)) was used to compare these two estimates of the gas column density and to show the limits and merits of both.

From Fig. 22 we can deduce a number of qualitative points. We first note that apparently 12CO measurements are insensitive to low column density regions. Specifically, it appears that up to \(\sim 0.2\) mag of \(K\)-band extinction...
tinction the radio measurements are uniformly distributed around 0 K km s\(^{-1}\). The relatively small scatter observed in Fig. 22 up to 0.15–0.2 mag of extinction (cf. also Fig. 23) indicates that both methods considered here have small intrinsic internal errors.

At higher extinctions, and up to \(A_K \approx 0.6\) mag, we observe an almost linear relationship between the extinction and the \(^{12}\)CO measurements; correspondingly, the scatter in the plot increases significantly (see below). We note that the presence of a linear relationship between the CO integrated temperature and the NIR extinction (and thus the hydrogen projected density), although on a relatively small extinction range, is not obvious on the scales considered here and for non-virialized cloud systems (see Dickman et al. 1986). Finally, for \(A_K \gtrsim 0.7\) mag, the \(^{12}\)CO data appear to saturate to a constant value close to 30 K km s\(^{-1}\). This well-known saturation effect is described in terms of an exponential relation between the integrated temperature \(I_{^{12}\text{CO}} \propto 1 - e^{-\tau}\) and the cloud optical depth \(\tau \propto A_K\). The following analysis will mostly focus on the unsaturated \(^{12}\)CO regime and will thus directly make use of the integrated temperature.

A more quantitative analysis of Fig. 22 was carried out as follows. We divided the measurements in regular bins in \(A_K\) (we used a bin size of 0.1 mag), and we computed in each bin the average of the \(^{12}\)CO intensity. The results obtained are shown as filled squares in Fig. 22. This simple plot confirmed the qualitative remarks discussed above and suggested that we could approximate the \(A_V-^{12}\)CO relationship with a function of the form

\[
I_{^{12}\text{CO}} = A \left[ \frac{1}{1 + \exp\left[-(A_K - A_{^{12}\text{CO}}^{\text{mid}})k\right]} - b \right], \quad (14)
\]

We fitted this equation to the data by minimizing the scatters between the predicted CO integrated intensity and the observed one; the best fit parameters obtained were \(A = 32.3\) K km s\(^{-1}\), \(A_{^{12}\text{CO}}^{\text{mid}} = 0.51\) mag, \(k = 6.20\) K km s\(^{-1}\) mag\(^{-1}\), and \(b = 0.036\). The residuals of this fit with the data are shown in details in Fig. 23. The increase of the dispersion in the relation (14) at \(A_K \approx 0.2\) mag is evident from this plot. Since the expected error in the Nicer map of Fig. 21 is as low as \(\sim 0.01\) mag, and since the expected error in the \(^{12}\)CO integrated velocities is also relatively small (this can be estimated from the residuals at \(A_K \approx 0\) mag of Fig. 23), we can deduce that the scatter shown in Fig. 23 for \(A_K > 0.2\) mag is physical: the ratio of dust and \(^{12}\)CO in the Pipe (and likely in other molecular clouds) is far from being constant.
So far we investigated the $A_K$-12CO relationship using the value of $A_K$ as independent quantity: in other words, we studied the expected CO measurement for each given $A_K$ column density. We now swap the role of $A_K$ and CO, and consider the average $A_K$ value corresponding to a given 12CO measurement. To this purpose, we averaged the values of the NICER extinction in bins of 5 km s$^{-1}$. The result, shown in Fig. 24, suggests that we can well approximate the average with a linear relationship of the form

$$A_K = A_K^{(0)} + r I_{12CO}. \quad (15)$$

Note that we need to include explicitly a non-vanishing “zero point”, $A_K^{(0)}$, for the $A_K$ measurement. This is due the dissociation of the CO molecule by the interstellar UV radiation field. Our results indicate that CO molecules in the Pipe become (self-) shielded from the interstellar radiation field at about 1 magnitude of visual extinction (2 magnitudes along the entire line of sight through the cloud), consistent with standard theoretical predictions and prior observations (e.g., van Dishoeck & Black 1988, Alves et al. 1999, Bergin et al. 2002). This CO threshold should in principle be a function of the intensity of the local interstellar radiation field and could in principle vary from cloud to cloud. We stress that it is highly unlikely that the NICER technique overestimates the extinction at low $A_K$, i.e. that the “zero point” observed in the relation 15 is an artifact; rather, if there is a bias in NICER, this is likely to be toward an underestimate of the column density (because of a possible reddened control field).

Our data, combined with the 12CO data, allows for the best determination of the CO-to-H$_2$ conversion factor (X-factor) using dust as a tracer of H$_2$, because of the large number of measurements (approximately 5 000) and also because our (smoothed) dust extinction measurements have a mean error smaller than 0.05 magnitudes of visual extinction. To derive the X-factor for the 12CO data we performed several best fits using Eq. (15) using different selections of the points of Fig. 24 and also because our (smoothed) dust extinction measurements have a mean error smaller than 0.05 magnitudes of visual extinction. To derive the X-factor for the 12CO data we performed several best fits using Eq. (15) using different selections of the points of Fig. 24 and the 12CO intensity.

Finally, Fig. 25 shows the residuals obtained from the fit of Eq. (15). Interestingly, these residuals appear to be rather constant on the field, and their standard deviation is approximately 0.1 mag in K-band extinction (or about 1 magnitude of visual extinction): hence, a single pointing in 12CO can only constrain the dust column density with an accuracy of a few magnitudes. Remarkably, this result is consistent with that found by Lada et al. (1994) for 12CO in the molecular cloud IC 5146, Alves et al. (1999) for 18CO in L977, and Bergin et al. (2002) for the molecular cloud Barnard 68. Hence, we find what it seems to be an irreducible uncertainty in the dust-CO correlation of about 1 magnitude of visual extinction. The cause for this irreducible uncertainty is not known and it deserves a dedicated study. A possible origin for this uncertainty might lie in the sensitivity of the CO molecule (and its isotopes) to variations in temperature (even along the same line-of-sight), density and UV radiation field (e.g. Freking et al. 1982, van Dishoeck & Black 1988). We note however that changes in the abundance of 12CO, due to freezing out on grains, are probably not in place at the extinctions less than $A_K \sim 1$ mag considered here when comparing the NANTEN and 2MASS/NICER analyses.

In order to further test this point, we considered the difference between the NICER extinction and the 12CO integrated intensity. In particular, we converted the degraded $A_K$ NICER extinction map shown in Fig. 24 (right) into a 12CO intensity using Eq. (14), and subtracted from this map the NANTEN 12CO extinction map. The result obtained, shown in Fig. 26, gives insight into the origin of the scatter observed in Fig. 24. The first striking fact is that clear structures are observed in Fig. 26 and this alone rules out the possibility that the difference between the 2MASS-NICER and the NANTEN measurements is...
due to statistical errors. Instead, in large areas we observe systematically positive or negative values of the difference between the two maps.

In analysing Fig. 26 one should always keep in mind that this map has been built by converting the NICER column density into a radio intensity by using the best fit provided by Eq. (14); hence, differences have to be interpreted as deviations from the fit used. With this point in mind, we can deduce some interesting facts from Fig. 26.18

- The outer regions of the nebula appear to have consistent measurements in radio and NIR. Given the form of Eq. (14), this further confirms that $^{12}$CO observations are insensitive to low column densities.

- In many peripheral parts of the Pipe nebula, the $^{12}$CO intensity appears to overestimate the (converted) NICER column density (see, e.g., the dark region in the middle of Fig. 26). This effect, in principle, could be related to differences in the photo-dissociation of CO molecules due to variations of the local interstellar radiations field. However, since generally an excess of $^{12}$CO intensity is observed in the periphery of the Pipe, it is more likely that the effect is related to temperature gradients in the nebula (this is also suggested by the patchy aspect of the map of Fig. 26).

- The dense cores (e.g., Barnard 59) generally appear bright in Fig. 26, indicating that the $^{12}$CO map underestimates the column density there when compared to the NICER analysis. This effect is clearly due to the saturation effect of $^{12}$CO at high column densities (the saturation hence appears to be even stronger than suggested by Fig. 22 and by the fit (14)).

### Table 2. Best fit parameters relative to Eq. (16).

| Fit                   | $A_{K}^{(0)}$ (mag) | $r$ (mag K$^{-1}$ km$^{-1}$ s) |
|-----------------------|---------------------|--------------------------------|
| Whole sample          | 0.176               | 0.0184                         |
| $t_{^{12}CO} > 5$ K km s$^{-1}$ | 0.199 | 0.0172                         |
| $A_{K} > 0.1$ mag     | 0.211               | 0.0165                         |
| $A_{K} < [0.1,0.6]$ mag | 0.226             | 0.0127                         |

The cloud mass $M$ can be derived from the $A_{K}$ extinction map using the following simple relation

$$M = d^2 \mu \beta_{K} \int_{\Omega} A_{K} d^2 x,$$

where $d = 130$ pc is the cloud distance, $\mu$ is the mean molecular weight corrected for the helium abundance, $\beta_{K} \simeq 1.67 \times 10^{22}$ cm$^{-2}$ mag$^{-1}$ is the ratio $N(H_1) + N(H_2)/A_{K}$ (Savage & Mathis 1979; see also Lilley 1955; Bohlin et al. 1978), and the integral is evaluated over the whole field $\Omega$. Assuming a standard cloud composition (63% hydrogen, 36% helium, and 1% dust), we find $\mu = 1.37$ and a total mass $M = (11000 \pm 2600)$ M$\odot$. The error is mainly due to the uncertainty on the distance of the cloud. Note that in this analysis we only included measurements above $b > +3^\circ$ (see discussion above in Sect. 6).

Our mass estimate apparently compares well with the independent one of Onishi et al. (1999), $M \simeq 10^{4}$ M$\odot$. Note, however, that if we use the cloud distance assumed by Onishi et al. (1999), $d = 160$ pc, we obtain a larger mass, $M = 1.7 \times 10^{4}$ M$\odot$, i.e., the CO derived mass is only about 65% the dust derived mass. As discussed in Sect. 6 this discrepancy can in principle be attributed to (1) the insensitivity of $^{12}$CO to low column densities, (2) to the saturation of $^{12}$CO in the dense cores of the cloud, and (3) to a relatively small X-factor used by Onishi et al. (1999). We can rule out the latter as the X-factor used by Onishi et al. (1999) $(2.8 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s) is virtually coincident (96%) with the one derived in this paper $(2.91 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s).

To investigate the source of discrepancy in the mass estimates we present in Fig. 27 the relationship between the integrated mass distribution and the extinction in $A_{K}$. We also plot, as a dashed line, the smoothed and clipped extinction map that was compared to the CO data (see Fig. 21). Note that regions with extinction larger than $A_{K} > 0.6$ magnitudes (where the CO-dust correlation breaks at higher column densities) account for about 20% of the total mass (dashed line). Similarly, note how regions with $A_{K} < 0.25$ mag, the column density threshold below which CO is not sensitive to H$_2$, account for about 15% of the cloud mass. The total fraction of dust mass that is missed by the CO is then about 35%, which, within the approximations, solves the discrepancy found between the dust and CO derived mass.

### 7. Conclusions

The main results of this paper can be summarized as follows:

- We used 4.5 million stars from the 2MASS point source catalog to construct a $8^\circ \times 6^\circ$ extinction map of the poorly studied Pipe nebula, a molecular cloud complex seen in projection towards the galactic bulge. The map...
The cumulative mass enclosed in isoextinction contours. The plot has been constructed using only extinction measurements at galactic latitude $b > 3^\circ$ (cf. Fig. 20). The solid line shows the cumulative mass from the whole NICER map, the dashed black line the cumulative mass from the downgraded (and clipped) map of Fig. 21 right, and the dashed grey line the cumulative mass derived from the NANTEN observations (see Fig. 21 right). For this latter mass estimate we used the conversion formula (15).

We studied in details the statistical properties of the extinction map obtained through the NICER method. We also confirmed the relation originally observed by Lada et al. (1994) for IC 5146, suggesting that there is unresolved structure at the highest extinctions in our map.

We compared our near-infrared study with the CO observations of Onishi et al. (1999), and derived fit formulae to relate the $^{12}$CO column density with the $A_K$ extinction. We also derived the dust-to-$^{12}$CO ratio, and showed that if a normal infrared reddening law is assumed, then the derived X-factor is as large as $2.91 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s in the range $A_K \in [0.1, 0.6]$ mag.

We found that $^{12}$CO is only sensitive to about 65% of the total dust mass. About half of the missing mass is not traced by CO at column densities below $A_K > 0.25$ mag, and half is not traced at column densities above $A_K > 0.6$ mag, where the line begins to saturate. There is an apparently irreducible uncertainty in the dust-CO correlation of about 1 magnitude of visual extinction. This uncertainty seems to be independent of the cloud or the interstellar radiation field.

– We took advantage of the large number of background sources to accurately measure the NIR reddening law for this cloud, and obtained $E(J - H) = (1.85 \pm 0.15)E(H - K)$, in very good agreement with the standard Rieke & Lebofsky (1985) reddening law.

– Finally from analysis of the JHK color-color diagram for the Pipe region we identify a large population of red stars whose colors are distinct from those of typical reddened background giants. These stars are spatially distributed over the entire observed field, preferentially located at lower Galactic latitudes and are not associated with the molecular cloud. These stars are the brightest stars detected in the field and have a very narrow distribution in magnitude space. These properties are similar to those of Galactic OH/IR stars. Our observations thus appear to have provided one of the largest samples of such stars yet discovered.

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