3D maps of the local ISM from inversion of individual color excess measurements

R. Lallement1, J.-L. Vergely2, B. Valette3, L. Puspitarini1, L. Eyer4, and L. Casagrande5

1 GEPI Observatoire de Paris, CNRS, Université Paris Diderot, Place Jules Janssen, 92190 Meudon, France
e-mail: [rosine.lallement; lucky.puspitarini]@obspm.fr
2 ACRi-ST, 260 route du Pin Montard, 06904 Sophia Antipolis, France
e-mail: jeanoluc.vergely@latmos.ipsl.fr
3 Institut des Sciences de la Terre, IRD: UR219, Université de Savoie, CNRS: UMR 5275 LGIT-Savoie, 73376 Le-Bourget-du-Lac, France
4 Observatoire de Genève, Université de Genève, Chemin des Maillettes 51, 1290 Sauverny, Switzerland
5 Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, The Australian National University,
ACT 2611 Weston Creek, Australia
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ABSTRACT

Aims. Three-dimensional (3D) maps of the Galactic interstellar matter (ISM) are a potential tool of wide use, but accurate and detailed maps are still lacking. One of the ways to construct the maps is to invert individual distance-limited ISM measurements, a method we have applied here to measurements of stellar color excess in the optical.

Methods. We assembled color excess data together with the associated parallax or photometric distances to constitute a catalog of ≃23 000 sightlines for stars within 2.5 kpc. The photometric data are taken from Strömgren catalogs, the Geneva photometric measurements, and the Geneva-Copenhagen survey. We also included extinctions derived towards open clusters. We applied an inversion method based on a regularized Bayesian approach to this color excess dataset, a method previously used for mapping at closer distances.

Results. We show the dust spatial distribution resulting from the inversion by means of planar cuts through the differential opacity 3D distribution, and by means of 2D maps of the integrated opacity from the Sun up to various distances. The mapping assigns locations to the nearby dense clouds and represents their distribution at the spatial resolution that is allowed by the dataset properties, i.e. ≃10 pc close to the Sun and increasing to ≃100 pc beyond 1 kpc. Biases toward nearby and/or weakly extincted stars make this dataset particularly appropriate to mapping the local and neighboring cavities and to locating faint, extended nearby clouds, which are both goals that are difficult or impossible with other mapping methods. The new maps reveal a ≃1 kpc wide empty region in the third quadrant in the continuation of the so-called CMA tunnel of the Local Cavity, a cavity that we identify as the Superbubble GSH238+00+09 detected in radio emission maps and that is found to be bounded by the Orion and Vela clouds. The maps also show an extended narrower tunnel in the opposite direction (l ≃ 70°) that also extends the Local Bubble further and together with it forms a conspicuous cavity bounded by the main Lup, Sco, Oph, Aql, Lac, Cep, and Tau clouds and OB associations. This chain of cavities and surrounding dense regions constitute the first computed representation of the well known Gould belt/Lindblad ring structures. Finally, almost all off-plane faint features that appear in 2D dust maps have a counterpart in the 3D maps, providing the dust distribution in nearby tenuous clouds.

Key words. local interstellar matter – dust, extinction – ISM: bubbles – ISM: clouds

1. Introduction

While emission surveys at various wavelengths are providing increasingly detailed maps of interstellar matter (ISM) in the Galaxy, they lack precise information on the distance to the emitting clouds. In particular, distance assignment based on their radial velocities and a mean Galactic rotation curve leads to a poor 3D description of the ISM in the Sun’s vicinity, while most of the medium and high-latitude emissions originate in this vicinity.

Other ways to obtain realistic 3D distributions of the ISM is to gather absorption data toward target stars located at known and widely distributed distances and to invert those line of sight data in some way. Absorption data may be gaseous lines that provide absorbing columns of gaseous species or color excess measurements that provide extinctions and dust columns. In the case of reddening data, they can be derived in a statistical way from stellar photometric surveys by means of color–color/color–magnitudes diagrams or stellar population synthesis and Galactic models (in particular the Galactic model of Robin et al. 2003), or they can be based on individual stellar reddening values, themselves based on photometric or spectrophotometric measurements and appropriate calibrations (see Marshall et al. 2006, 2009; Sale & Drew 2010; Gontcharov 2012; Chen et al. 2013; Knude 2010; Cambrésy et al. 2011; Reis et al. 2011; Knude & Lindström 2012, for details on various data and methods). In the absence of parallax measurements, photometric distances are derived along with the reddening in a consistent way, or distances are estimated by comparing the density of foreground stars with models (as in Lombardi et al. 2010). Those methods based on large surveys have the strong advantage of being based on a huge amount of targets, however the achievable spatial resolution is limited due to the required statistics and most of those techniques are not appropriate for mapping at small distance due to the need for zero reddening references.
Those methods that are based on individual sightlines can potentially produce a higher radial spatial resolution (in principle only limited by the mean radial distance between two target stars) and are appropriate for the solar neighborhood. However, there is not much data available today, and those maps are still restricted to the Sun’s vicinity. This situation will hopefully change in future thanks to data from high-resolution multiplex spectrographs and from the ESA astrometric mission Gaia, and for this reason it is useful to investigate inversion techniques and their application to individual reddening data of increasing number, which is the focus of the present work.

The first attempt to compute a 3D distribution of the ISM by inverting individual line-of-sight data was made by Vergely et al. (2001), who used compiled data on neutral interstellar (IS) absorbers (NaI and HI), as well as the corresponding Hipparcos parallaxes, and inverted those individual data using a robust tomographic method (Tarantola & Valette 1982). Lallement et al. (2003) gathered data for the specific purpose of mapping the so-called Local Bubble or Local Cavity, a 100–200 pc-wide cavities are the dense cloud associations. More recently, Vergely et al. (2003) gathered data to form density maps around the Sun, and applied the same method to a larger NaI dataset (around 1000 sightlines) with Hipparcos distances. It confirmed the view that there is a cavity that is deficient in cold and neutral interstellar gas and that the closest dense and cold gas is at ~80 pc (Cox & Reynolds 1987). The inverted map also revealed interstellar tunnels that connect the Local Bubble to surrounding cavities. High-latitude sightlines with the smallest absorption are found in chimneys, whose directions are perpendicular to the Gould belt plane. The maps show that the Local Bubble is squeezed by surrounding shells in a complicated pattern. Welsh et al. (2010) presented 600 pc wide NaI and CaII maps using a catalog of absorptions towards 1857 early-type stars located within 800 pc of the Sun. While NaI traces dense and neutral IS, CaII traces both dense neutral and ionized gas. The CaII exhibit strong spatial similarities to those of their equivalent NaI absorption maps, since the dominant features are the dense cloud associations. More recently, Vergely et al. (2010) has developed the inversion method further, and updated the sodium maps and inverted ~6000 extinction measurements based on stellar Strömgren photometry and stars possessing Hipparcos parallaxes. The similarity between the locations of the major dust clouds deduced from the extinction inversion and the gas clouds deduced from NaI within 250 pc has been a first test of the inversion method. Most features, the main opaque regions, the Local Cavity boundaries, and the tunnels to surrounding cavities were also derived by Reis et al. (2011) from Strömgren photometry measurements and reddening-distance relationships. See also Reis et al. (2011) for a general review of solar neighborhood mapping, by means of any method.

Here we extend the inversion and the mapping to greater distances by making use of more distant stars and by merging target stars possessing Hipparcos parallaxes and targets with photometric distances. Section 2 describes the data used for the inversion. In Sect. 3, we briefly describe the improved inversion method and discuss its parameters. In Sect. 4, we present the resulting 3D distributions by means of separate planar cuts. In Sect. 5 we show distance-limited 2D reddening maps based on the inverted 3D distribution and integration up to spheres of various radii. We discuss the results in Sect. 6.

2. Color excess data and distances

We started with the Vergely et al. (2010) $E(b - y)$ dataset, i.e., color excesses derived from Strömgren photometry for nearby stars possessing Hipparcos parallaxes measurements. We used parallax values here and associated errors from the most recent analysis of van Leeuwen (2007). The types were distributed between B0 to G2, with 60% of F-G types.

We added to this list reddening and photometric distances derived self-consistently from Geneva photometric measurements for a large dataset of B stars (Cramer 1999; Burki & Cramer, priv. comm., see the Geneva photometric database). The catalog is composed of early-type stars, O, and a large majority of B-type stars. There are 614 targets in common with the Strömgren-based dataset, and they were used to establish the relationship between the Strömgren $E(B - V)$ and the Geneva $E(B - V)$ color excess values. This relationship, already described in Raimond et al. (2012) was found to be $E(B - V)_{\text{Geneva}} = (1.585 \pm 0.0129) E(b - y) + (0.0221 \pm 0.0007)$. Thus, we converted the Geneva $E(B - V)$s into $E(b - y)$s following this relationship, then converted all $E(b - y)$s into Johnson $E(B - V)$s following the relationship $E(B - V)_{J} = 1.335 E(b - y)$. In the case of repeating stars, we chose to use the Strömgren and Hipparcos distances.

We then added the catalog of color excess and distances derived for the target stars from the latest revision of the Geneva-Copenhagen Survey (Nordström et al. 2004; Casagrande et al. 2011). The catalog is composed of late-type stars, mainly F and G stars. The reddening estimates are based on the intrinsic color calibration of Olsen (1988), which has a stated accuracy of ±0.01 mag. Similar to the former catalogs, such observational errors might lead to negative values of reddening for nearby stars that have zero or very weak reddening. We removed stars already contained in the two other catalogs. Finally, we used color excess measurements towards a series of stellar clusters, as well as the best estimates of the cluster distances, all from the recent new catalog of Dias et al. (2012).

All extinction measurements were scaled to the Johnson system. For the last three sources, we used the photometric distances, even for stars possessing a Hipparcos parallax, since they were derived self-consistently along with the extinction. All those datasets were filtered for known binaries in cases of potentially affected extinction and distance derivations. For all datasets we kept the negative values of the color excess, in order to avoid any statistical bias at a short distance. We then retained from this merged list only those stars fulfilling the following conditions: estimated distance below 2500 pc, estimated distance to the plane smaller than 300 pc, $E(B - V)_{J} \geq -0.02$ (see below), and relative uncertainties on the distances smaller than 35% for both Hipparcos and photometric distances. The limitation in distances is guided by experience. Keeping a few isolated, very distant stars with uncertain distance provides weak additional constraints resulting in elongated structures of poor interest (see the map descriptions). On the other hand, using a threshold on the relative uncertainty allows maintaining moderately distant targets that have a particularly good accuracy and to exclude those nearby stars that have very large uncertainties. The limitation in height above the plane results in a limited distance for the inversion that is a function of the latitude, more precisely $d_{\text{lim}} = 300/(\sin(b))$. We come back to this point in Sect. 4. Our final list contains 22 883 remaining targets: 5106, 12 120, 4830, and 827 targets are from the four sources.

3. The inversion method applied to extinction data

The present inversion is based on the pioneering work of Tarantola & Valette (1982) who derived general formalisms for nonlinear, least squares inverse problems. We use here their specific formalism adapted to the solution for functions of continuous variables. In our context the differential reddening (or,
equivalently, differential opacity) is a continuous function of the 3D interstellar space. Given our datasets of distance-limited data, reconstructing such a 3D map is by far underconstrained. However, the inversion can be regularized and performed by requiring that the solution is smooth and by using a Bayesian formulation; i.e., the solution is based not only on the color excess data but also on prior knowledge of the opacity distribution (see Vergely et al. 2010). These two information sources complement each other; where the constraints from the data are insufficient, the inversion restores the prior density; in the opposite case, it favors the information contained in the data. For more details on the inversion technique applied to IS line-of-sight data, see Vergely et al. (2010). We mention hereafter the specific changes from this previous work.

3.1. Data and associated errors

The data are the color excess measurements toward the target stars and the target distances. It is important to determine their biases and standard deviations. The color excess is assumed to be proportional to the dust opacity toward the target. At variance with the previous inversion, we make use of independent color excess datasets that are not based on the same wavelength coverage or intrinsic dispersion in the color-magnitude diagrams. It is important that in case of HIPPARCOS or cluster data, as mentioned above, we removed all targets for which the relative error exceeds 35%. This is important for HIPPARCOS parallaxes, since it is well known that the accuracy may drop strongly for distant stars (≥300 pc). Also, errors on photometric distances to the clusters are not independent, which may introduce stronger discrepancies than in groups of independent stars in the same region.

3.1.2. Distances

Uncertainties on the distances are crucial for the inversion process. Relative errors on the distances are either the HIPPARCOS errors in the case of parallax measurements, or arbitrarily taken to be 20% for all photometric determinations, except for the cluster distances for which Dias et al. (2012) provided conservative estimates. It is important that in case of HIPPARCOS or cluster data, as mentioned above, we removed all targets for which the relative error exceeds 35%. This is important for HIPPARCOS parallaxes, since it is well known that the accuracy may drop strongly for distant stars (≥300 pc). Also, errors on photometric distances to the clusters are not independent, which may introduce stronger discrepancies than in groups of independent stars in the same region.

3.1.3. Propagated errors

During the inversion, quantities that are computed and adjusted are integrated quantities along pathlengths, and as a consequence, errors on those integrals arise from both extinction and distance uncertainties. For this reason they are not treated independently during the inversion (see Vergely et al. 2010). In the present work, the total errors σtot on the integrated opacities toward the targets have been taken to be the quadratic sum of three terms:

\[ \sigma_{\text{tot}} = \sqrt{\sigma_{\text{phot}}^2 + \sigma_{\text{cal}}^2 + \sigma_{E_d}^2} \]

i) \( \sigma_{\text{phot}} \) is the extinction measurement error quoted above;

ii) \( \sigma_{\text{cal}} \) is an additional error equal to 0.01 to represent uncertainties linked to the use of different photometric systems and calibration methods (see above); and

iii) \( \sigma_{E_d} \) is the error on the distance \( d \) propagated to the extinction \( E(B-V) \), estimated to be \( \sigma_{E_d} = E(B-V) \frac{\sigma_d}{d} \) under the assumption of a constant opacity along the LOS. We also assume that \( \frac{\sigma_d}{d} = \sigma_L \) for HIPPARCOS parallaxes \( \pi \).

About the assumption that \( \sigma_{E_d} = E(B-V) \frac{\sigma_d}{d} \), it may appear highly questionable to assume a constant opacity given the strong clumpiness of the ISM. However, the combined errors are used in the model computation, in the frame where IS matter is much more smoothly distributed than in the actual medium. This makes the assumption significantly more realistic. Moreover, as \( d \) increases, \( \frac{\sigma_d}{d} \) increases but the assumption generally does not become more invalid, since the smoothness and structure size also increase with distance as a result of the target scarcity. Finally, if there are strong incompatibilities between some data due to this assumption, uncertainties are accordingly increased during the iteration process (see the Appendix).

3.2. Prior information on the model and associated variances

Here the model parameters are functions. We define the correlation kernel \( \psi(x, x') \) as the correlation of the opacity between two points in space \( x \) and \( x' \). It is fundamental since it controls the spatial variability of the model, the shape of allowed structures, and the smoothing length. Evidently the smoothing length

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cannot be shorter than the average distance between the targets, here varying between a few pc to ≃100 pc depending on the distance from the Sun and the location, otherwise the problem is too under-constrained.

Making use of a simple Gaussian kernel, \( \psi(x, x') = \exp\left(-\frac{1}{2} \frac{(x-x')^2}{\xi_0^2}\right) \), where \( \xi_0 \) is the smoothing length, yields a poor fit that we interpret as the consequence of the ISM clearly showing different characteristic lengths. It is thus well-advised to use multiscale kernels (Serban & Jacobsen 2001; Vergely et al. 2010). Vergely et al. (2010) used two exponential kernels, the first one characterizing the warm diffuse matter and the second one the more compact clouds. However, the smallest structures (pc and sub-pc scale) cannot be represented because the spatial fluctuations that are smaller than the smoothing length are not detected.

After a number of tests, we chose the following two kernels as best representing the different scales that can be detected given the dataset. They have two different functional forms to produce both an exponential wing and a Gaussian core. The exponential law is appropriate in the case of multiscale structures, and it allows the intercloud phase and large scales to be reproduced. On the other hand the Gaussian kernel allows to reach denser structures, while introducing a threshold in their sizes to avoid too much power in unrealistic, very small, and dense structures. The final choice was finally based on the quality of the adjustments. The kernel is expressed as

\[
\sigma(x)\sigma(x')\psi(x, x') = \sigma_0(x)\sigma_0(x') \frac{1}{\cosh(-x/\xi_0)} + \sigma_1(x)\sigma_1(x') \exp\left(-\frac{x^2}{\xi_1^2}\right)
\]

where \( \sigma_0^2(x) \) represents the model variance at point \( x \) that controls the departures from the prior distribution, and \( \xi_{(0,1)} \) are the characteristic scales allowed in the model. Parameters are given in Appendix A.

In addition, the density of IS matter decreases strongly with the distance to the Galactic plane. The prior model is therefore characterized by an exponential decrease with the distance to the plane \( \rho_{\text{ref}}(r, b) = \rho_0 \exp\left(-\frac{r}{\rho_0}\right) \). Following Vergely et al. (2010), we chose to use \( \rho_0 = 200 \text{ pc} \) for the opacity scale height, a value deliberately above the average measurement (Chen et al. 1998) to avoid the loss of the tenuous high-latitude structures during the inversion, which may happen when the prior density is too low. Finally, the computed variable is the logarithm of the opacity per distance \( \rho(x) = \exp(\alpha(x)) \) to ensure the positivity of the solution.

4. Results

The line of sight data are inverted to produce a tridimensional differential opacity distribution in a Sun-centered volume whose total dimensions are \( 4 \times 4 \times 0.6 \text{ kpc}^3 \), with 0.6 kpc the vertical extent, i.e. 300 pc above and below the horizontal plane containing the Sun (for simplicity we call Galactic plane this horizontal plane, despite the non-zero distance of the Sun to the actual plane). However, only for about half of this volume is the model significantly constrained, since the target stars are too sparse at a large distance where the opacity distribution remains equal or very close to the prior model, and for this reason the results presented below are restricted to the central regions. To better illustrate the limits of the inversion a \( b = 0^\circ \) planar cut in the full inverted volume is shown in the appendix (Fig. A.1). We also illustrate in an appendix the distribution of stars that are close to the plane and that constrain the distribution. The reason for maintaining targets as distant as 2500 pc during the inversion is that they may contribute to the constraints at closer distance, e.g. in the case of very low reddening, and they may reveal some
trends. The inverted quantity is the smoothed reddening per distance, here \( E(B-V) \) in magnitude per pc (color scale in Fig. 1). The map can be used to estimate the total reddening toward a target contained in the represented plane, by using the color scale and the Sun-target trace on the map. For clarity in the maps, we have added a few annotations. We recall that (mainly distant) regions where the distribution looks fully homogeneous and varies as a function of only \( Z \) are those for which the prior distribution has been unchanged, owing to the lack of constraining targets. We use the Galactic plane map to discuss the uncertainties associated to the inversion method.

4.1. Extinction in the Galactic plane

Figure 1 shows the color-coded differential opacity distribution in the plane. We have added iso-differential opacity contours in order to enhance the characteristics of the distribution. We warn the reader again about the impact of the correlation kernel on the actual values of the differential opacity: high numbers, that would correspond to the densest structures and cloud cores, are not reached anywhere, but instead the inverted quantity corresponds to an average over regions of size on the order of 15 or 30 pc. Still, the color-coded map allows the reddening to be estimated up to a given distance.

It is informative to compare this updated map with the former map of Vergely et al. (2010) based on about a quarter of the present dataset, and we present such a comparison for the Galactic plane. This is illustrated in Fig. 2 where we have superimposed on the new map an iso-differential opacity contour computed from the 500 pc wide former map. The differential opacity value that has been chosen for this iso-contour, namely \( dE(B-V)/dr = 0.0002 \) mag per pc corresponds to the marked transition between the Local Cavity and its boundaries. It can be seen that this contour is quite similar to the new Local Cavity boundary now found in the inner part of the new map. The new boundary is traced by the first new contour (thin red line) that has been drawn for \( dE(B-V)/dr = 0.00016 \) mag per pc. Hatched areas show the locations of the dense clouds that came out from the previous inversion. It can be seen that, while those areas still correspond to dense regions in the new, more extended maps, the clouds now often extend to greater distances. The reason is that regions beyond the first opaque clouds were simply not showing up previously due to the lack of constraining target stars, because those stars were too extinguished, hence absent from the dataset. Instead the prior distribution was kept in those external regions. These limitations still exist for the new maps, albeit now pushed away at larger distances. This is why we call attention on the fact that dense structures at large distance and located exactly beyond other, closer dense clouds may be underestimated or even missing in the maps.

To quantify the limitations from the limited number of distant targets, we show in Fig. 3 the achievable resolution at each location in the plane resulting from the target distributions. There are strong asymmetries between the quadrants that reflect the mentioned biases and the predominance of empty or dense areas. We also display in Fig. B.1 (resp. B.2) of the appendix those stars that are within 10 (resp 150) pc from the Galactic plane and are the main contributors to the opacity pattern, superimposed on the Galactic plane map itself. This comparison allows us to figure out at which distance and in which direction constraints are getting too loose and the prior solution is preferred. It is also a way to figure out the minimum size of the structures that can be reconstructed during the inversion from the distance between the targets. It can be seen that the minimum size increases from \( \approx 10 \) pc close to the Sun (see Fig. B.1) up to \( \approx 150 \) pc at 1 kpc (see Fig. B.2). Errors on the locations of the clouds depend on the target distribution and evidently distance uncertainties, but are difficult to quantify. If a structure is defined by a statistically significant number of targets, errors on the distances average out and the center of the structure is correctly defined. The extent of the clouds, however, increases as a result of all distance uncertainties. In case only a few targets define a structure, there may be very different errors among the various situations. If the targets are angularly close but have different distances, the model produces radially elongated structures that
are easily identified, and the radial size of those structures allow inferring the error on the cloud location. If targets are both scarce and irregularly located towards a structure, e.g., if they are missing towards the densest area, then individual errors on distances may have their strongest impact; i.e., the error on the cloud location may reach the mean error on the target distances. Fortunately, this is not the case for most of the clouds.

The map reveals the top or bottom parts of the series of dense structures that bound the so-called Local Cavity, the \( \approx 100 \) pc wide empty region around the Sun: the Aquila, Ophiuchus, Scorpius, Lupus, Crux, and Centurus dense clouds in the first and fourth quadrants; the Cassiopeia, Lacerta, Perseus, Taurus, and Orion clouds in the anti-center area. It is beyond the scope of this article to discuss those clouds in details; instead, we only superimpose the major cloud complexes and OB associations on the series of vertical maps presented in the next section. The distribution in Fig. 1 shows a conspicuous, huge empty cavity in the third quadrant. This cavity is in the continuation of the so-called CMa tunnel, the rarefied region that extends up to 130–150 pc in the direction of the star \( \epsilon \) CMa. A dense region located at \( \approx 180 \) pc marks a partial limit between the two cavities, but it is angularly limited. As shown in other planar cuts, this huge cavity is not limited to the plane but extends both above and below to large distances. We note that the existence of this cavity has been inferred by Heiles (1998) based on radio maps and other emission data. The schematic representation of GSH238+00+09 by Heiles (1998) corresponds quite well to the geometry that is coming out from the inversion. As already noted in this work, this super-bubble is bounded by the Orion clouds at lower longitude, and by Vela clouds at \( \approx 260–270^\circ \).

Fig. 4. Opacity distribution in vertical planes containing the Sun, equally spaced by 15°. The north pole direction \( b = +90^\circ \) is at the top and longitudes of intersections with the Galactic plane are indicated. Some iso-differential opacity contours have been superimposed to help visualize the low- and high-opacity regions. OB associations from De Zeeuw (1999), as well as CO and HI clouds listed by Perrot & Grenier (2003) have been displayed when they are within 25 pc of this vertical plane. We also add the molecular cloud locations derived by Knude (2010). The tenuous cloud close to the north pole direction.