Methods to account for interstellar extinctions

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GAIA-CUO-093 September 7, 2001

Abstract. A detailed knowledge about the galactic extinction is mandatory to obtain the astrophysical/kinematical parameters time variation outside the solar neighborhood. One may hope that the GAIA photometry itself will contribute color excesses for most of the sample otherwise the extinction must be deduced from external sources. 3D galactic models where the dust distribution is an integral part seems a viable solution. Some information may be obtained even from a color vs. distance diagram.

1. Introduction

Since GAIA is an astrometric/photometric/spectroscopic mission aiming mainly at understanding the composition, formation, evolution and gravitational potential of the Galaxy the astrophysical requirements to the medium band photometry are quite severe. In order to model the Galaxy's evolution metallicities, effective temperatures and ages must be known with accuracies better than a few tenths of a dex, a few hundred degrees Kelvin and some hundred million years, respectively. Color indices must accordingly be observed with a precision better than ≈ 0.02 mag and the transformation to intrinsic indices (classification), ideally for any stellar type, on the same level of accuracy. This implies almost perfect correction for interstellar extinction. The amount and location of the obscuring interstellar material is best known in the immediate solar vicinity but only for the most diffuse part of the medium ($A_V \leq 2$ mag) much less is known about the galactic distribution of the extinction taking place in the molecular clouds ($A_V \geq 2-3$ mag). We review some recent extinction data and 3D modelling of the extinction distribution and propose a new simple method applying the GAIA parallaxes that possibly may be used to provide a coarse 3D extinction map. This may be useful since a result from the preliminary discussion of the accuracy of the photometric systems suggested for GAIA indicates that even a coarse limitation of the reddening range improves the accuracy of the remaning parameters, Vansevicius (2001). From our simple ISM modelling it seems possible to extract some information on the parameters of the diffuse reddening from the (V-I) vs. distance

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diagram such as the maximum and the most probable reddening per unit distance.

2. Dust on different scales

In Table 1 of Perryman et al (2001) the primary galactic kinematic tracers are listed together with the relevant range of visual extinctions expected. From this table we note the expected range of A_V is 0 – 10 mag. Extinction determinations on the required accuracy level include correction for varying chemical composition and gravity implying that high quality photometry in the ultraviolet and violet bands must be available. This may be a serious problem for the high extinctions $A_V \geq$ 2 – 3 mag. Consequently it could be necessary to introduce alternative, probably less precise methods to correct for large extinctions. If the inversion techniques applied to reconstruct the density field from the distance – column density data can be refined to reproduce even small spatial features, $\phi \approx 0.5$ pc, one could hope that the parallax together with the reconstructed 3D field may provide extinctions of a sufficiently high quality even for interesting peculiar stars.

The main source for the extinction should of course be the GAIA photometry itself and the photometric determination of the reddening is not a trivial matter, Vansevicius (2001). The extinction study by Sudzius et al (2001) indicates that individual reddenings may be obtained if the matter distribution is not too complex. A photometric 8 band system proposed for FAME is claimed to estimate effective temperature and extinction with a precision of 1 – 2%, Olling (2001).

To have an overview of various external extinction indicators we briefly address the following items listed in the table below:

(1) An example of the use of the dust emission in the IRAS bands for an all sky extinction determination may be found in Schlegel et al (1998), we get the well known impression that dust seems ubiquitous. Recently Drimmel and Spergel (2001) presented a new 3D model for the Galaxy where the dust distribution was modelled from far and near infrared emission from the COBE/DIRBE instrument. The "galactic" dust distribution introduced by Spergel and Drimmel indicates the high degree of sofistication that must be included in models of the diffuse, virtually continous part of the galactic dust.

Before launch of the GAIA mission we may probably expect rather detailed information on the all sky local dust emission from the various FIR – mm bands included in the MAP and Planck missions. Column densities from the cosmic background missions may provide a good comparison to the optical extinction resulting from GAIA. In addition to the smoothly varying galactic models based on the galactic structure parameters any model must also account for local deviations.

There is a long tradition to derive structure parameters by comparing deep CCD photometry to model predictions. These Galaxy models include a dust distribution, Bienaymé, Robin and Crézé (1987). A major challenge is how to account for local deviations to the double exponentional often applied, see Ojha (2001).

The DENIS and 2MASS surveys are also quite useful for studying the galactic dust. Ruphy et al (1997) applied a smooth dust distribution to correct the DENIS J and K_S counts for a comparison to a model of the predicted infrared point source counts. Ojha (2001) used 2MASS data for a study of the galactic thin and thick disk and assumed the smooth diffuse dust distribution to be like the young thin disk but also introduced individual absorption features.

(2) An early investigation of the extinction's distribution over several kpc is given by Klare and Neckel (1980), resulting maps may also be found in Hakkila et al (1997) a synthesis of published studies. Open clusters often have well determined distances and extinctions, facts used by Chen et al (1998) to reproduce the 3D A_V/pc field within ≈ 2 kpc and at low galactic latitudes. The density field is determined with an inverse method. Given the rather small number of open clusters the spatial resolution is limited. Chen et al also present an extinction – distance law for every 10 degrees along the galactic plane. Jønch-Sørensen (1994) have presented E_{b-y} vs. distance diagrams for about ten small regions. The data are based on *uvbyβ* CCD photometry of A, F and G type stars brighter than V ≈ 19 mag. Most of the directions observed penetrate the galactic dust disk but the data probably only pertain to the more diffuse part of the interstellar medium, $A_V \leq 2 - 3$ mag. GAIA results are expected to be of similar or better accuracy than the *uvbyβ* results. Better since the parallax is determined independently and because the GAIA photometry will be useful for a wider spectral type range than *uvbyβ*, see Vansevicius *op.cit.*

(3) Discussion of the Galaxy's bulge requires very deep photometry and even the windows with the least extinction has $A_V \approx 2$ mag. Ng and Bertelli (1996) present a discussion of the possible distribution of the extinction. Similar considerations may apply for GAIA data on the inner regions of the Galaxy.

(4) Star counts may probably be used to derive extinctions through molecular clouds. Cambrésy (1999) used the USNO-PMM catalogue for star counts and a wavelet decomposition to derive extinctions. Maximum extinctions beyond $A_V \approx 25$ mag are indicated for some molecular cores. Due to the sharp distribution of near infrared colors of dwarf stars a straightforward determination of the near infrared color

Table I. Dust on various scales

(1)	The Galaxy	(a) infrared emission: IRAS, COBE/DIRBE, MAP, Planck
		(b) optical stars counts
		(c) infrared stars counts
(2)	The galactic plane	(a) O and B stars
		(b) galactic clusters
		(c) CCD data of faint A, F and G stars
(3)	The galactic bulge	(a) broad band CCD data
(4)	Molecular clouds	(a) USNO-PMM counts
		(b) broad band CCD color counts
		(c) H, J, K photometry
(5)	The solar vicinity	(a) Hipparcos parallaxes and NaI D absorption
		(b) parallaxes and $uvby\beta$ measurements
		(c) parallaxes, Tycho photometry and classification
(6)	The galactic poles	(a) A and FG stars
(7)	gas emission	(a) 21 cm emission/absorption
		(b) HI and molecular gas

excesses is possible for molecular clouds, Lada et al (1994), but V and I counts may probably also be used as shown by Thoraval et al (1997). Due to the large ratio $\frac{A_{\rm V}}{E_{\rm H-K}} \approx 16$ the demands to the precision of the H, J, K photometry are extreme for correction of individual field stars.

(5) The solar vicinity is of particular importance not least since it may represent a low density cavity. Local extinction measurements are preoccupied with defining the edge of this cavity and to search for possible clouds inside it. Sfeir et al (1999) have combined NaI D absorption lines with Hipparcos parallaxes to construct iso-column density contours. Similar data were used by Vergeley et al (2001) but with an inversion method to establish the density field within a few hundred pc. It is interesting to note that virtually none of the structures identified by Vergeley et al are present in Chen et al's density map but also that nearby features like the Chameleon clouds are missed

by their grid. If some classification may be provided, it need not be perfect and could come from Q – Q diagrams, the distance to extinction discontinuities may be identified. Knude and Høg (1998) showed that even with Michigan classification, Tycho photometry and Hipparcos parallaxes distances to nearby molecular clouds could be estimated.

(6) Last we mention the rather complex color excess distribution towards the NGP. This high latitude extinction is caused by matter closer than $\approx$ 200 pc, it seems that only about 1/3 of the polar cap is screened by clouds with excesses exceeding about E_{b-y} = 0.030 (A_V $\approx$ 0.1 mag), Knude (1996). The local bubble may accordingly not have a completely coherent confinement, an impression one might get from the NaI D iso contours, Sfeir et al (1999).

The reality of the isolated, low color excess clouds, at high and intermediate latitudes, are confirmed from observations at UV and infrared wavelengths, see e.g. Haikala et al (1995) and Berghöfer et al (1998).

(7) A further complication may have arisen with the recent revelation of a hitherto rather unnoticed population of HI clouds by the the 1 arcmin beam survey of the galactic plane, Gibson et al (2000). Some of the clouds showing HI absorption are proposed to have diameters $\sim$0.5 pc and the majority has no CO emission counter parts, a rather peculiar combination. It is essential to investigate the frequency of these clouds both for the sake of extinction correction but also for understanding the structure of the Galaxy's extinction distribution. It seems important to put some emphasis on investigating the linear scales on which the extinction displays major variation.

With a known gas/dust ratio and the known gas distribution A_V may be estimated at any (l, b, d(pc)), Otriz and Lépine (1993).

3. Inversion models

A substantial fraction of the GAIA targets will have accurate parallaxes, mainly the brighter part of the sample, but it is assumed that even the faintest stars will have acceptable photometric parallaxes, $\frac{\Delta d}{d}$ $\leq$ 20 – 30 %. The astrometry may, however, be of such high quality that the trigonometric parallax is more precise than the photometric parallax, even at the survey limit. We will thus have a very detailed combination of extinctions and distances which may be used to establish a 3D distribution of some parameter measuring the interstellar volume density. Recently there has been some papers presenting the results of inverting the column density – distance information to a 3D density field (Chen et al (1998), Arabadjis and Bregman (2000), Vergely et al (2001)). In particular the maximum entropy reconstruction by Arabadjis and Bregman seems to be promising, their method have not been tested on real data so far. Chen et al present a galactic extinction law for the Galaxy's plane, to which their extinction probes are confined, that may be compared to independent data. This comparison emphasizes the importance of a good angular resolution, apparently rather local molecular densities are missed by the model – this stresses the need to have a good knowledge of the model opacity $\rho_{op}(l,b,r)$ and the different scale heights of the distribution of diffuse and molecular material (120 – 140 and 40 – 50 pc respectively). The opacity $\rho_{op}(l,b,r)$, or ρ_0 cm^{-3} (or A_V/pc) for the diffuse medium will vary with position as may be seen on Fig. 12 in Jønch-Sørensen (1994). The extinction tracers in the GAIA sample on which emphasis should be put could be chosen from considering their ability to determine the input parameters for the inversion codes – like ρ_0, h_Z and h_R. This request could influence the choice of medium band filters. Are the information obtainable from O, B and A stars adequate or must stars with higher spatial densities, G and K, be preferred?

4. Extinction from two broad bands and GAIA parallaxes

The 3D mapping of the interstellar density is facilitated by the large number of stars per square degree resulting from the GAIA mission. Within 5 degrees from the galactic plane we may expect more than 5000 stars per square degree. We may probably define solid angles (rather small indeed) so that significant parts of the main sequence may be populated at most distances. We may chose two wide bands, e.g. like V and I, and form a representative main sequence $(V\text{-}I)_0 - M_V$ relation, could be done with unreddened GAIA data. We then select a distance d pc (parallax) and include all stars in the range d$\pm$0.10d pc. We may then investigate if any stars at d$\pm$0.1d have a common extinction A_V. If this is the case they must be located on a locus: the main sequence relation shifted by $V - M_V = A_V - 5 + 5\log d$ and the color shift given by $\Delta(V\text{-}I) \equiv E_{V-I} = A_V(1\text{-}\frac{A_I}{A_V})$ implying that the extinction law must also be known. The distance error from such fits are 10 – 20%.

Stars at a common distance and with a common extinction must be located on a shifted main sequence relation, just like clusters. So this is "main sequence fitting" to field stars. Contours with a 3σ separation $A_V \sim 0.2$ mag may be expected from such a method, almost meeting the requirements for studying the Galaxy's evolution. We have applied a similar method to the CG 30 complex of cometary globules and to the Lupus 2 cloud (Knude and Nielsen (2000), (2001)). And we have

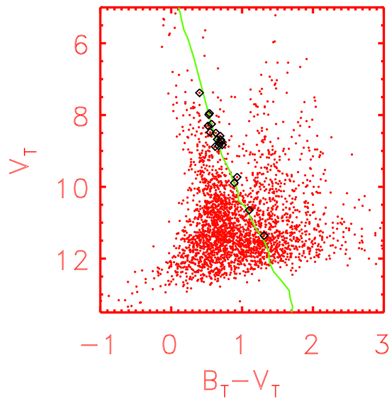

Figure 1. Tycho-2 photometry and Hipparcos parallaxes. Data pertain to the region α_{2000} = 40.0 – 51.0 (deg), δ_{2000} = 14.0 – 23.0 (deg) covering the three molecular clouds MBM 12, 13 and 14. The curve is the $(B_T - V_T)_0$ vs. M_{V_T} relation shifted to 75 pc with $A_{V_T} \approx 0.15$ mag. Diamonds indicate stars also in the Hipparcos Catalog and with $(B_T - V_T)$ within ±0.030 mag from the shifted main sequence

performed sort of a test in the vicinity of the very local molecular cloud MBM 12 , 13, 14 with the Tycho-2 photometry, Høg et al (2000), and Hipparcos parallaxes, ESA (1997), Knude and Fabricius in preparation:

Figure 1 is the Tycho-2 color − magnitude diagram covering these three nearby molecular clouds. In the diagram we see features resembling main sequences protruding to the blue and bright part of the diagram. It is checked whether the features are due to known clusters in the region under study. If not we try to fit the features with the $(B_T - V_T)_0$ vs. M_{V_T} relation established from nearby, presumably unreddened stars common to the Tycho-2 and Hipparcos catalogs. As for clusters the fit provides the distance d(pc) and the absorption A_{V_T}(mag). A fit to a feature is indicated by the solid curve in Fig. 1. Now a fraction of the bright Tycho-2 stars is in the Hipparcos Catalog and we extract those that futhermore have $(B_T - V_T)$ within ±0.03 mag from the fit in Fig. 1, these stars are shown as diamonds in Fig. 1. The main sequence fit suggest a distance of 75 pc and $A_{V_T} \approx 0.15$ mag.

19 stars fulfil the criteria mentioned above, their mean parallax is 11.44±4.93 mas ranging from 3.09 to 20.24 mas. The mean implies a distance of ∼87 pc. These stars are of course a mixture of dwarfs and giants, for our fit we assumed they were all dwarfs. The giant contamination may not be too serious because the colors of most of the stars fitted are bluer than $(B_T - V_T) \sim 0.8$, about where the unreddened giants starts showing up. For the GAIA sample the parallax

is known for all stars! If we exclude stars more than one standard deviation from the mean, 12 stars remain with a mean $\pi = 11.92$ mas and the error of the mean is 0.70 mas. A common distance d $\sim 84 \pm 5$ pc is thus suggested. The median parallax of all 19 stars is 11.17 mas corresponding to 90 pc. Within the errors the two distance estimates are identical. For MBM 12 Hearty et al (2000) find a distance range 58 – 90 pc from a combination of NaI D spectroscopy and Hipparcos parallaxes. The lower distance limit just indicates the most distant star in front of MBM 12 not showing measured NaI D absorption. The upper distance limit from this study is indentical to our suggested distance.

This means that choosing a constant parallax, the GAIA stars with a given absorption must lie on a shifted main sequence and their location on they sky will trace the corresponding absorption contour. Combining these contours for varying distance may probably provide a coarse 3D dust distribution.

One must necessarily study the reddening and distance effects of the main sequence width and the influence of metallicity on the intricsic main sequence relation.

5. Models and simulations

We have constructed a simpel ISM – model with three structural components: a diffuse component with small discrete features of constant reddening distributed randomly with five features per kpc. At each distance one may compute the probability of any reddening according to Poisson statistics. Next a sheet with homogeneous reddening located at some fixed distance. Thirdly a molecular cloud where the distance, central reddening and density profile is chosen. The spatial distribution of the stellar tracers follows the luminosity function of Cox (2000) for dwarf stars in the galactic plane, each absolute magnitude is assigned an intrinsic color. Stars are distributed randomly in space. With GAIA the distance is known independently of the photometry. The errors on measured color and distance are assumed to be randomly gaussian. It turns out that the molecular cloud is easily located by varying distance and reddening as discussed in the previous Section.

The small reddenings caused by the diffuse component is much more problematic. But as Fig. 2 shows the general appearance of reddening vs. distance, as measured with ground based photometry is reproduced qualitatively. If the reddening is not known information on the statistics may be extracted from observed color vs. distance diagrams as Fig. 3. The bulk of stars in the disk is located around the turn off and have accordingly rather similar intrinsic colors. These could then be expected

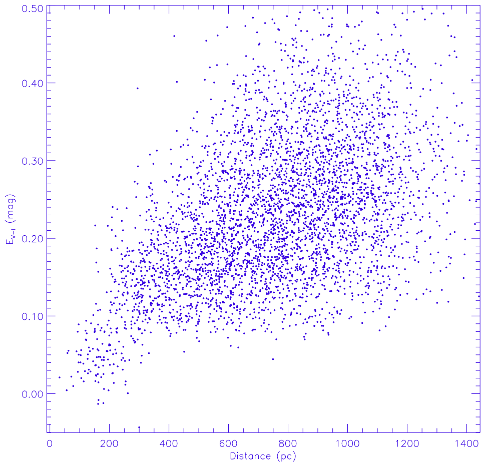

Figure 2. Color excess vs. distance from sheet and discrete diffuse clouds

to display a trend caused by the most probable reddening in a color vs. distance diagram. In Fig. 3 the solid indicates this trend for stars with $(V\text{-}I)_0 \approx 0.9$ reddened by a sheet and the discrete features. The dashed line is the maximum reddening expected from Fig. 2, the slope is taken from the upper left envelope in Fig. 2. What is observed is Fig. 3. If we make a color histogram a each distance the bluest maximum indicates the color of the turn off stars (intrinsic plus reddening). The slope of this maximum's variation with distance is the reddening per unit distance, provided the turn off has a well defined color. Similarly the maximum diffuse reddening at a given distance may be deduced from the location of the variation of the minimum in the color histograms when the distance is increased. The upper envelope in Fig. 3 is mainly caused by the sample's limiting magnitude which is chosen to V = 19. Diagrams like Fig. 3 may probably also be used to approximate reddening law variations discernible if diagrams are produced for various colors. The GAIA wide bands may be of use for this purpose.

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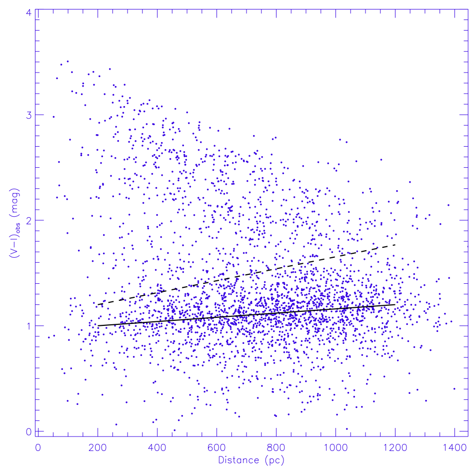

Figure 3. Observed color vs. measured distance (GAIA). The solid line indicates the trend of the most probable reddening at each distance. The dashed line is the maximum diffuse reddening at each distance. The upper envelope is due to the limiting magnitude V = 19

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