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Constraining galactic structure parameters from a new extinction model and four star count samples

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Abstract. We propose a new 3-dimensional extinction model based on the COBE/IRAS all sky reddening map. Its application to globular and open cluster data evidences that the COBE/IRAS reddening map has an accuracy of 18%, but overestimates visual absorption by a factor of 1.16. This systematic error does not change with galactic latitude and opacity significantly.

The implementation of the new extinction model has optimized our galactic structure and kinematic model to low-galactic latitudes. Four star count samples distributed in different galactic directions have been compared with galactic model simulations. Numerical experiments allow us to constrain the radial distribution of the galactic disk. The disk scale length is found to be 2250 $\pm$ 50 pc and the displacement of the Sun from the galactic plane $Z_{\rm Sun}$ = 27.5 $\pm$ 6.0 pc.

Key words: ISM: dust, extinction – Galaxy: globular clusters: general – Galaxy: open clusters and associations: general – methods: statistical – astronomical data bases: miscellaneous – Galaxy: solar neighbourhood

1. Introduction

The interstellar extinction is of crucial importance on many fields of optical astronomy. However, the 3-dimensional distribution of the extinction $A_{\rm v}(r, l, b)$ is only known in the solar neighbourhood. FitzGerald (1968) maps interstellar extinction using color excesses of 7835 O to M stars. Neckel & Klare (1980) derived extinctions and distances for more than 11000 stars and investigated the spatial distribution of the interstellar extinction at $\mid b \mid < 7.6^{\circ}$. Using a larger sample (about 17000 stars) with MK spectral types and photoelectric photometry, Arenou et al. (1992) published an extinction model in which the sky was divided into 199 cells. Recently, Méndez & van Altena (1998) and Chen et al. (1998b) have constructed interstellar extinction models of the solar neighbourhood.

All extinction models mentioned above are valid not far away from the Sun ($r < 2$ kpc). In order to estimate galactic absorption for remote cluster galaxies, Sandage (1972) has used a modified cosecant law. This extinction model has been widely used in the Bahcall & Soneira (1980) Galaxy model for large-scale sky simulation for HST observations and deep star count analysis. Another large-scale extinction model has been published by Hakkila et al. (1997), who have combined previous investigations on extinction distribution and made a statistical correction for distances at which the studies do not provide data. This large-scale extinction model cannot reproduce low extinction values known to exist in some directions of galactic windows and the extinction errors in the model are often large (Hakkila et al. 1997).

Galactic structure studies involve the analysis of star count observations and their comparison with Galactic model simulations. Most of the previous comparisons between observed and predicted star counts have avoided the low-galactic latitude regions, where the distribution of the interstellar reddening is not well known. Bahcall & Soneira (1984) have compared the results from their Galactic model with 17 high-latitude star count samples, Reid & Majewski (1993), Ng et al. (1997) and Chen (1997) have investigated the galactic structure toward the galactic pole. Robin et al. (1996) have analyzed star count data in a number of galactic directions with $\mid b \mid > 20^{\circ}$. Buser et al. (1998) have analyzed seven Basel high-latitude field star count survey to constrain the thick disk parameters.

On the other hand, low-latitude star count analysis is interesting on constraining the radial distribution of galactic stars, and for evaluating the expected number of stars. As examples, Méndez & van Altena (1998) and Robin et al. (1992) have investigated the scale length of the galactic disk from low-latitude star count observations. Franceschini et al. (1991) have estimated the diffuse starlight in the galactic plane based on the galaxy model of Bahcall & Soneira (1980). However, due to the intrinsic uncertainty on extinction at low galactic latitudes, discrepant results on the disk density scale length have been found (from 2.5 kpc (Robin et al. 1992) to 6.0 kpc (Méndez & van Altena 1998)).

In this paper, we propose a new 3-dimensional extinction model $A_{\rm v}(r, l, b)$ based on the COBE/IRAS reddening map (Sect. 2). In Sect. 3, the accuracy of the proposed extinction model is tested using globular and open cluster data.

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In Sect. 4, four star count samples at different galactic directions have been compared with the simulated data from our galactic model improved at low galactic latitudes by the implementation of the new extinction model. We summarize our results in Sect. 5.

2. Large-scale extinction model

Recently, Schlegel et al. (1998, hereafter SFD) published a full-sky map of the Galactic dust based upon its far-infrared emission. The IRAS experiment gives high angular resolution at 100 μm, where the DIRBE experiment provides the absolute calibration necessary across several passbands to map the dust color temperature and convert 100 μm emission to dust column density. Point sources and extragalactic sources are removed as much as possible. This dust map is normalized to $E(B-V)$ reddening using the colors of background galaxies. The spatial resolution is about 6.1 arcmin. This map is intended to supersede the Burstein & Heiles (1982) map in both accuracy and spatial resolution.

Two important simplifying assumptions are made in the SFD work: 1) all of the dust is at one single temperature and, 2) the dust temperature is measured with the 40 arcmin beam of DIRBE. Both approximations are valid at high latitudes – low opacity cirrus – but not for large extinctions at intermediate and low latitudes, where molecular gas contributes significantly to the IR emission and the dust emission spectrum is not well fitted by a single temperature (Reach et al. 1995; Lagache et al. 1998).

The SFD map gives, by its construction, a total dust emission (converted to reddening) along a given line of sight, so it does not provide the interstellar extinction as a function of distance r from the Sun. To do that, following Méndez & van Altena (1998), we assume $F_\lambda(\boldsymbol{r})$ be the flux measured from a source by an observer, and F_λ^o the flux in the absence of extinction, then we have $F_\lambda(\boldsymbol{r}) = F_\lambda^o \exp(-\tau_\lambda(\boldsymbol{r}))$, where $\tau_\lambda(\boldsymbol{r})$ is the optical-depth (Spitzer 1978). Then the absorption suffered by the light from this source is given by $A_\lambda(\boldsymbol{r}) = -2.5\log(\frac{F_\lambda(\boldsymbol{r})}{F_\lambda^0}) \sim 1.086\tau_\lambda(\boldsymbol{r})$

According to Mihalas & Binney (1981), the optical-depth $\tau_\lambda(\boldsymbol{r})$ is usually expressed in terms of the number volume density of the absorbing material $n(\boldsymbol{r})$ and the average extinction cross-section k_λ via the equation:

$$\tau_\lambda(\boldsymbol{r}) = k_\lambda \int_0^{|\boldsymbol{r}|} n(\boldsymbol{r}')d|\boldsymbol{r}'| \quad (1)$$

Suppose that the large-scale volume density of the absorbing material, $n(\boldsymbol{r})$, follows a decaying exponential law away from the galactic plane, as given by:

$$n(\boldsymbol{r}) = n_\mathrm{o}\exp(-\mid Z \mid / h_\mathrm{red}) \quad (2)$$

$$Z \; = \; Z_\mathrm{Sun} + r \, \sin b \quad (3)$$

where Z_Sun is the distance of the Sun from the galactic plane, and h_red is the scale height of the absorbing material.

Sandage (1972) has assumed a scale height of 100 pc for this medium. This value was also used by Parenago (1945) in

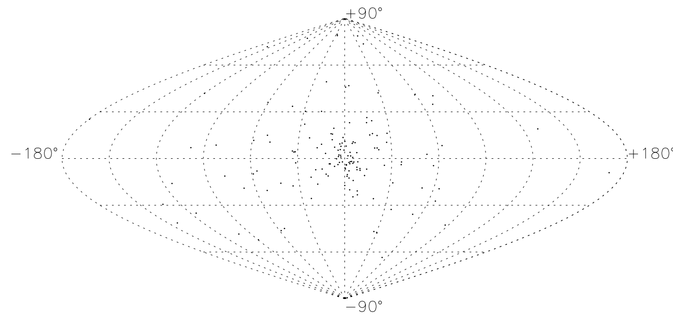

Fig. 1. The distribution of the known globular clusters in the Milky Way

his pioneer work. However, Scheffler & Elsasser (1987) have obtained thicknesses of about 130 to 150 pc from measurements of cold diffuse HI; Solomon et al. (1979) found h_red = 65 pc from a compilation of different CO surveys, and Spitzer (1978) estimates h_red = 100 pc from the statistical properties of the dust layer within 1 kpc of the Sun. As a compromise value between all these determinations, we adopt h_red= 100 pc in this study.

From Eqs. (1), (2) and (3), we can derive the reddening via the equation:

$$\frac{E(B-V)(r,l,b)}{E(B-V)(\infty,l,b)}$$
$$= 1-\exp\left(-\frac{r\mathrm{sin}b}{h_\mathrm{red}}\right) \quad \text{if} \quad b \geq 0^\circ$$
$$\frac{1-\exp(-\frac{r\mathrm{sin}b}{h_\mathrm{red}})}{1-2\exp\left(\frac{Z_\mathrm{Sun}}{h_\mathrm{red}}\right)} \quad \text{if} \quad b < 0^\circ \quad \text{and} \quad r|\sin b| \leq Z_\mathrm{Sun}$$
$$\frac{1-2\exp\left(\frac{Z_\mathrm{Sun}}{h_\mathrm{red}}\right)+\exp\left(\frac{2Z_\mathrm{Sun}+r\mathrm{sin}b}{h_\mathrm{red}}\right)}{1-2\exp\left(\frac{Z_\mathrm{Sun}}{h_\mathrm{red}}\right)}$$
$$\text{if} \quad b < 0^\circ \quad \& \quad r|\sin b| > Z_\mathrm{Sun} \quad (4)$$

$E(B-V)(\infty,l,b)$ is the reddening at "$r = \infty$", which is obtained directly from SFD map. These equations were derived by assuming the Sun is above the galactic plane, but similar equations can be obtained if the Sun is below it.

From now on, we refer this extinction distribution (Eq. (4)) as NCI (New COBE/IRAS) extinction model. We want to emphasize that, according to Eq. (1), this model assumes a constant absorption coefficient along the line of sight, that is, we are making the crude approximation that the distribution of absorbing material is homogeneous along the line of sight. The uncertainties in this approximation will be evaluated in Sect. 3.5.

3. Comparison of NCI extinction model with observations

3.1. Globular clusters

Harris (1996) published a catalog of galactic globular clusters with reasonably well-known properties. The catalog contains basic parameters – distances, reddening, metallicities, luminosities, colours – and dynamical parameters for 147 objects regarded as globular clusters in the Milky Way. In Fig. 1, we

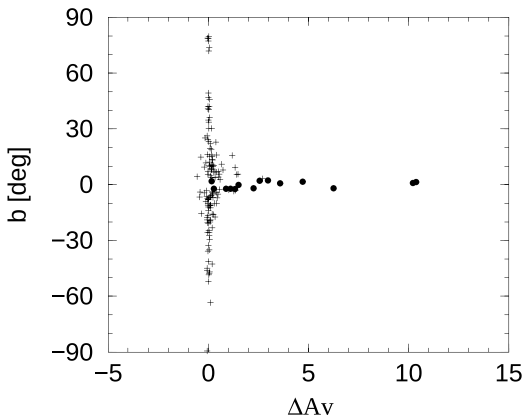

Fig. 2. Deviation $\Delta A_{\rm v} = A_{\rm v}(NCI)-A_{\rm v}$(obs) for globular clusters as a function of galactic latitude b. Solid circles are clusters with $\mid b \mid< 2.5°$.

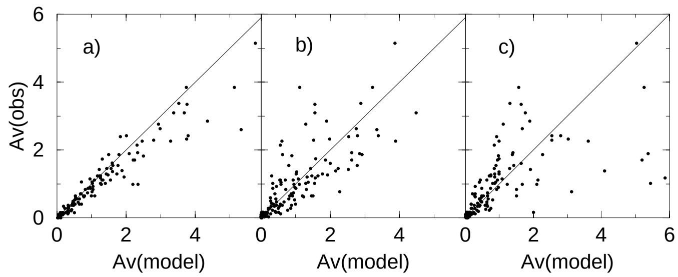

Fig. 3a–c. The observed extinction $A_{\rm v}$(obs) from globular cluster at $\mid b \mid\geq 2.5°$ against predictions by several extinction models. **a**: NCI model for $Z_{\rm Sun}$ = 0, **b**: Sandage (1972) model, **c**: Hakkila et al. (1997) model. The ratio of total-to-selective absorption $R = 3.1$ was adopted to obtain $A_{\rm v}$(model) and $A_{\rm v}$(obs) from $E(B-V)$.

show the distribution of globular clusters in Harris's sample. It can be seen that the clusters are mainly concentrated towards the galactic center. We excluded two globular clusters in Harris's sample, which have no distance information. For the remaining 145 clusters, the extinction $A_{\rm v}$(NCI) has been estimated from NCI extinction model.

In Fig. 2, we plot the deviations $\Delta A_{\rm v} = A_{\rm v}(NCI)-A_{\rm v}$(obs) as a function of b. The large deviations ($\Delta A_{\rm v}$) found for clusters with $\mid b \mid< 2.5°$ are a consequence of the simplifying assumptions already mentioned in Sect. 2 and to the fact that most contaminating sources at low galactic latitudes could not be removed from the reddening map (SFD). For these reasons, we limit our comparison to the region with $\mid b \mid\geq 2.5°$. Thus 14 clusters with $\mid b \mid< 2.5°$ have been removed and our remaining sample includes 131 globular clusters, all with $\mid Z \mid$ height larger than the dust scale height (assumed to be 100 pc).

In Fig. 3 we compare the observed extinction $A_{\rm v}$(obs) from the globular cluster sample (obtained from Harris's catalogue) with NCI, Sandage and the Hakkila et al. extinction models, respectively. We can see that NCI model has a much smaller scatter than Sandage (1972) and Hakkila et al. (1997) extinction models. This is evidently due to the fact that Sandage model neglects interstellar extinction variation as a function of galactic longitude (l) and small-scale variations arising from dense interstellar clouds, and the Hakkila et al. model is mainly based on observational data within 1$\sim$2 kpc from the Sun. Hakkila et al. have added a statistical correction for large distance. Introduction of statistical extinction values at large distance from the Sun results in an increasingly poor approximation to the actual extinction distribution.

We have tested different displacements of the Sun from the galactic plane $Z_{\rm Sun}$ in NCI extinction model (Eq. (4)), and found that this parameter does not change the results of comparison for our globular cluster sample. This is because most globular clusters in our sample are at distance $r > 2$ kpc, so the exponential term in the NCI model is negligible and $A(r,l,b) \sim A_{\infty}(l,b)$.

From Fig. 3, we can also see that NCI extinction model overestimates the extinction. Using a linear fit to the globular cluster sample, we obtained $A_{\rm v}$(NCI)$= 1.16 A_{\rm v}$(obs)$+0.02$, indicating that the SFD reddening map overestimates extinction by a mean factor of 1.16.

3.2. *Open clusters*

In the open cluster Data Base (Mermilliod 1992) we found 412 open clusters with known reddening and distance. For the rest, we have checked the ADS database to see whether there are new observations published after 1992. We have found new data for 22 such clusters, mostly due to the observations from Padova and Boston groups (Friel 1995).

In order to check whether a systematic bias exists on the distances determined from photometric methods, Chen et al. (1998b) have compared the open cluster distance derived from Hipparcos data (Robichon et al. 1997; Mermilliod et al. 1997) with those in Mermilliod's open cluster database. No systematic trend has been found. We have also compared the $E(B-V)$ values quoted in Mermilliod (1992) with those of Dambis (1999) and no significant difference has been noticed.

Fig. 4 shows the observed extinction $A_{\rm v}$(obs) from 158 open clusters with $\mid b \mid\geq 2.5°$ against NCI, Sandage and Hakkila et al. models, respectively. In Fig. 4a and 4b, we show the results of tests of different displacements of the Sun, $Z_{\rm Sun}$, from the galactic plane in the NCI extinction model, we found that this parameter does not change the results significantly. Using a linear fit to the open cluster sample, and a robust estimation method (Morrison & Welsh 1989), we found that the SFD reddening map overestimates $E(B-V)$ by a factor of 1.18. This is in good agreement with the result from globular clusters obtained in the previous section.

3.3. *Burstein and Heiles reddening map*

We compared the SFD reddening map with the old reddening map made by Burstein & Heiles (1982, BH hereafter), which has been widely used by the astronomical community (one of the most cited papers). For this comparison, we have randomly created 2000 galactic positions (l, b) in the whole sky. The total reddening along a given line of sight is derived from SFD reddening map $E(B-V)$(SFD) and BH map $E(B-V)$(BH). Because the BH maps exclude all regions at $\mid b \mid< 10°$, as well

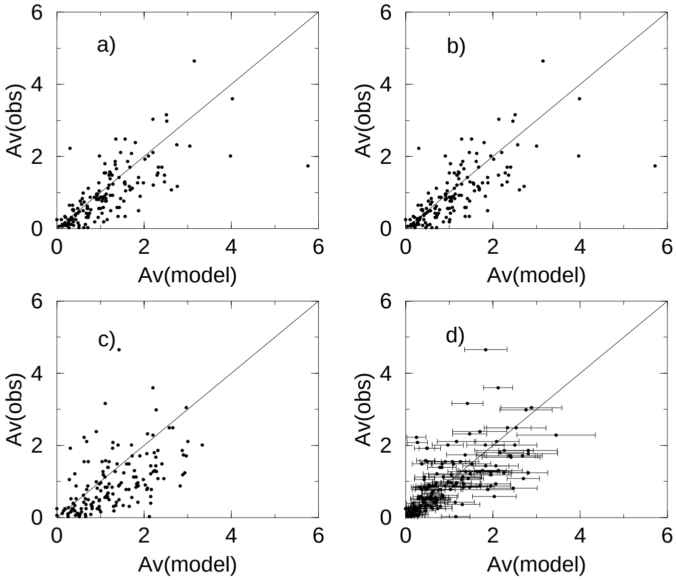

Fig. 4a–d. The observed extinction $A_{\rm v}$(obs) from open cluster dataset with $\mid b \mid\geq 2.5°$ against predictions by three extinction models: **a** NCI model with $Z_{\rm Sun}$ = 0, **b** NCI model with $Z_{\rm Sun}$ = 27.5 pc, **c** Sandage (1972) model, **d** Hakkila et al. (1997) model.

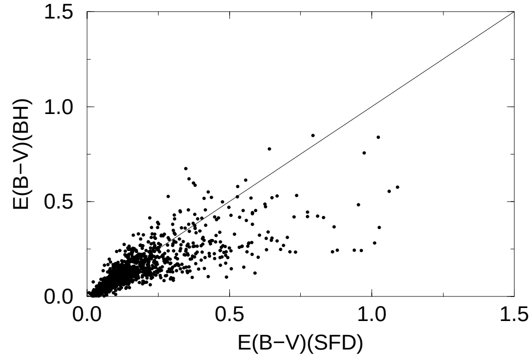

Fig. 5. $E(B-V)$(SFD) from SFD reddening map against that $E(B-V)$(BH) from the Burstein & Heiles map for 2000 simulated galactic positions (l, b), where BH estimate exists.

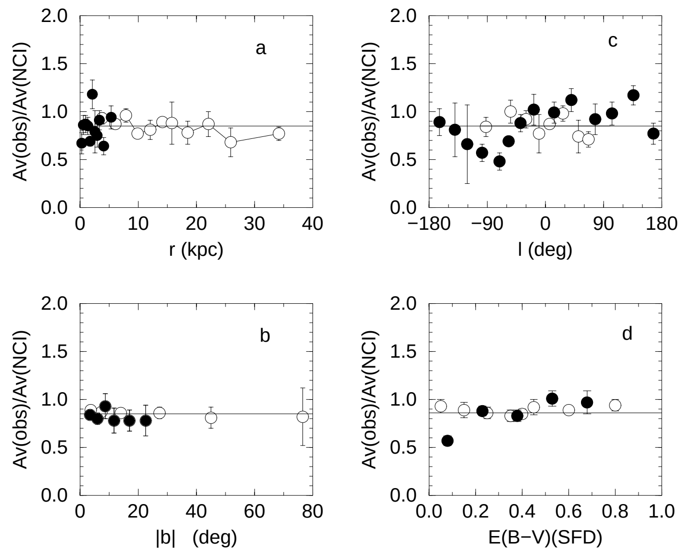

Fig. 6a–d. $A_{\rm v}$(obs)/$A_{\rm v}$(NCI) as a function of $(r, l, \mid b\mid, E(B-V))$. The solid lines are $A_{\rm v}$(obs)/$A_{\rm v}$(NCI)$= 0.86$. The open circles are the results from the globular cluster sample and the solid circles are that from open cluster sample, all with $\mid b \mid\geq 2.5°$.

as some regions lacking 21-cm data, we have excluded all galactic positions (l,b), where no BH estimate exists. From Fig. 5, we can see that the SFD reddening values are higher than those from BH map. Using again a linear fit, we obtained $E(B-V)$(SFD) = 1.15$E(B-V)$(BH). This is in very good agreement with the results from the globular cluster and the open cluster samples, indicating an overestimation on SFD reddening map. SFD have plotted a full-sky map of the SFD reddening estimate minus the BH estimate for the region $\mid b \mid> 10°$. In good agreement with our results, they found that the SFD reddening estimate is systematically larger than the BH reddening estimate by 0.02 mag in $E(B-V)$, and even more towards molecular clouds such as Orion and Ophiuchus.

3.4. Correction to NCI extinction model

In order to check if $\frac{A_{\rm v}(obs)}{A_{\rm v}(NCI)}$ is a function of the galactic longitude (l), latitude ($\mid b\mid$), the distance (r) from the Sun or the opacity, in Fig. 6 we plotted $\frac{A_{\rm v}(obs)}{A_{\rm v}(NCI)}$ as a function (l, $\mid b\mid$, r, $E(B-V)$) for the globular clusters (open circles) and the open clusters (solid circles). This is interesting because globular clusters can constrain the NCI extinction model at large distance and toward galactic center direction, and open clusters can test the extinction model at low-galactic latitudes inside the dust layer. The solid lines in Fig. 6 are $\frac{A_{\rm v}(obs)}{A_{\rm v}(NCI)}$ = 0.86. From Fig. 6a and 6b, we conclude that no significant systematic trend depending on distance or galactic latitude is present.

In Fig. 6c a clear dependence on galactic longitude is observed when working with the open cluster data (solid circles), with a significant deviation in the region $225° < l < 290°$. As pointed out by Guarinos (1992), between Orion and Sco-Cen complex, the interstellar medium is transparent around the Sun at least up to 1000–1400 pc. Thus, the fact that our extinction model assumes a constant opacity per unit distance along the line of sight, provokes the clear overestimation of the absorption in this region. Because the size of our observed samples is small, it is not possible to construct a specific extinction model in this low extinction region.

Special attention has been paid to analyze if a systematic change on the extinction calibration with opacity is observed. Considering the globular cluster data, in Fig. 6d we found a good alignment of the data around the line at 0.86, indicating that the 1.16 overestimation factor of the SFD calibration does not depend on the amount of absorbing material. Furthermore, we checked that the deviation in the first bin in Fig. 6d from open cluster data corresponds to the open clusters placed at $225° < l < 290°$ already discussed.

Stanek (1998a,b) has compared the SFD reddening map with the Harris's globular cluster sample. In the first paper, the author calculated the absolute difference on reddening and found that the SFD reddening map overestimates the reddening in some large extinction regions, obtaining not significant differences for $\mid b \mid > 20°$. Later (Stanek 1998b), using 19 globular clusters at $\mid b \mid \leq 5°$, he found that the SFD reddening map overestimates $E(B-V)$ by a factor of 1.35. As can be seen from Fig. 6b, our results do not corroborate this dependence on galactic latitude; on the contrary, a constant overestimation factor is obtained.

Recently, Arce & Goodman (1999) tested the SFD reddening map using the extinction study of a region in the Taurus dark cloud complex. They found that the SFD all-sky reddening map overestimates the reddening by a factor of 30%-50% in region of smooth extinction with $A_{\rm v} > 0.5$ mag. This factor is even higher than what we found (16%). However, their results are only in one galactic region.

From the above discussions and as a first approximation, an average overestimation factor of 1.16, derived from the results of globular cluster and open cluster dataset over all-sky, has been adopted and applied to SFD reddening map ($E(B-V)(\infty, l, b)$) in our NCI extinction model in order to fit the observations.

3.5. Error in NCI extinction model

To estimate the global error in the NCI extinction model we have proceeded in two steps. Because all globular clusters have a Z-height higher than the dust scale height, the distance uncertainty does not translate in any extinction error; thus, globular clusters have been used to estimate the extinction error at infinity derived from our re-calibrated SFD map. After the derivation of this contribution, the open clusters – located within the dust disk – have been used to estimate the uncertainty coming from the assumption of a constant opacity per unit distance along the line of sight.

Working with globular cluster data, the total extinction error ($\sigma_{\rm A_v}$(total)), derived as the standard deviation of the difference $A_{\rm v}$(obs)$-A_{\rm v}$(NCI), is assumed to come from both, the error in the observed reddening (Harris 1996) and the error coming from the NCI model. If we assume the calibration error on the observed absorption in Harris's catalogue approximately equal to 0.1 mag (see an exhaustive discussion in Webbink 1985), then we can get an error estimation on the re-calibrated SFD reddening map from:

$$\sigma^2_{\rm A_v}({\rm SFD}) = \sigma^2_{\rm A_v}({\rm total}) - \sigma^2_{\rm A_v}({\rm cal})$$

We have grouped our globular cluster sample into six groups according to $A_{\rm v}$(NCI). In Table 1, we show the number of clusters (N), the average $A_{\rm v}$(NCI), $\sigma_{\rm A_v}$(total) and $\sigma_{\rm A_v}$(SFD) from re-calibrated SFD map for each group. From Table 1, we can see that the extinction errors increase with $A_{\rm v}$(NCI). A least squares fit gives:

$$\sigma_{\rm A_v}({\rm SFD}) = -0.01_{\pm 0.04} + 0.18_{\pm 0.03} A_{\rm v}({\rm NCI})$$

SFD pointed out that their reddening map has an accuracy of 16% in predicting reddening, in very good agreement with our results (18%) and the dispersion shown in Fig. 3a. Our results also show that the accuracy of SFD reddening map, originally calibrated for low reddening region ($E(B-V) < 0.2$), can be used down to higher opacity regions ($E(B-V) \sim 0.8$).

Table 1. The extinction error in each group $A_{\rm v}$(NCI) from globular cluster sample

$A_{\rm v}$(NCI)	$\overline{A_{\rm v}(NCI)}$	$\sigma_{\rm A_v}$(total)	$\sigma_{\rm A_v}$(SFD)	N
0–0.3	0.15	0.10	0.00	43
0.3–0.6	0.45	0.15	0.11	20
0.6–0.9	0.78	0.12	0.06	15
0.9–1.2	1.08	0.21	0.19	15
1.2–1.8	1.49	0.33	0.31	15
1.8–2.7	2.15	0.37	0.36	12

Unlike globular clusters, most open clusters are located within the dust disk. Now, to the total extinction error we have to add the contribution due to the uncertainties on distance estimation and that produced by the assumption of a constant opacity per unit distance along the line of sight. Thus, the observational error on extinction from open clusters includes a calibration error approximately equal to 0.1 mag and a error due to the distance error. Assuming that the relative distance error is 0.25, we have:

$$\sigma^2_{\rm A_v}({\rm obs}) = 0.1^2 + (0.25 A_{\rm v}({\rm obs}))^2 \quad (5)$$

The error $\sigma_{A_{\rm v}}$(NCI) in our NCI extinction model can be written:

$$\sigma^2_{\rm A_v}({\rm NCI}) = \sigma^2_{\rm A_v}({\rm SFD}) + \sigma^2_{\rm A_v}({\rm opa}) \quad (6)$$

where $\sigma_{\rm A_v}$(SFD) is the error from the re-calibrated SFD map derived from globular cluster, and $\sigma_{\rm A_v}$(opa) is the error due to the assumption of a constant opacity per unit distance along the line of sight.

By combining Eqs. (5), (6) and the total extinction error $\sigma^2_{\rm A_v}$(total) = $\sigma^2_{\rm A_v}$(obs) + $\sigma^2_{\rm A_v}$(NCI), which is derived from the standard deviation of the $A_{\rm v}$(obs) - $A_{\rm v}$(NCI), we can estimate the error $\sigma_{\rm A_v}$(opa) in our extinction model.

The open cluster sample has been grouped into six groups according to $A_{\rm v}$(NCI). In Table 2, we show the number of clusters (N), the average $A_{\rm v}$(NCI), the total extinction error $\sigma_{\rm A_v}$(total) and $\sigma_{\rm A_v}$(opa). A least squares fit gives:

$$\sigma_{\rm A_v}({\rm opa}) = 0.09_{\pm 0.07} + 0.15_{\pm 0.06} A_{\rm v}({\rm NCI})$$

Therefore, the total relative error in extinction using NCI model for an object inside the dust plane can be estimated as $\sigma_{\rm A_v}$(NCI)/$A_{\rm v}$(NCI) $\sim$ (0.18^2 + 0.15^2)$^{0.5}$= 0.23 indicating that our model has a relative error of 23%.

4. Low-latitude star count analysis

The new extinction model (NCI) has been implemented in our Galaxy model software to estimate apparent magnitude and colour distributions in four low-latitude fields. The simulated values with different radial structure parameters are compared with the observed ones and the best-fitting model parameters are determined by a maximum likelihood technique.

Table 2. The extinction error in each group $A_{\rm v}$(NCI) from open cluster sample

$A_{\rm v}$(NCI)	$\overline{A_{\rm v}(NCI)}$	$\sigma_{A_{\rm v}}$(total)	$\sigma_{A_{\rm v}}$(opa)	N
0–0.3	0.19	0.11	0.00	26
0.3–0.6	0.47	0.25	0.18	26
0.6–0.9	0.81	0.40	0.30	31
0.9–1.2	1.09	0.49	0.31	25
1.2–1.8	1.49	0.60	0.36	27
1.8–2.7	2.17	0.72	0.33	15

4.1. Galaxy Model

A Galaxy structure and kinematic model has been constructed (Chen 1997). The model can generate ‘stars’ according to the selection criteria used in the observations. This model has been used to simulate the magnitude, colours and proper motions distribution in the North Galactic Pole (Chen 1997) and at the solar neighbourhood (Chen et al. 1998b) and to estimate the contribution of the field stars in the region of open cluster NGC 4815 (Chen et al. 1998a).

The method used in the Galaxy model is based on numerical integrations of the fundamental equation of stellar statistics for the j-th subsystem:

$$A_{\rm j}(V) = \omega \int \Psi_{\rm j}(M) D_{\rm j}(r) r^2 dr \quad (7)$$

where $A_{\rm j}(V)$ is the number of stars of a given apparent magnitude, $\Psi_{\rm j}$ (M) is the luminosity function, $D_{\rm j}(r)$, the density law and ω the field of view (solid angle) in the observing data. It can be seen from Eq. (7) that, in order to predict star counts in a given direction, one requires a luminosity function and a density law for each population or sub-population in the model. The detailed discussions of our Galaxy model can be found in Chen (1997), and its main structure parameters are given in Table 3.

In order to simulate the apparent magnitude distribution, the absolute magnitude ($M_{\rm v}$) must be transformed into V magnitude according to:

$$V = M_{\rm v} - 5 + 5\log r + A_{\rm v}(r,l,b) \quad (8)$$

where $A_{\rm v}(r,l,b)$ is the interstellar extinction distribution at the given galactic direction (l,b).

4.2. Star count observations

Four star count samples at low-galactic latitudes have been used to constrain the radial structure distribution of the galactic disk. Completeness limits, galactic directions, area coverage, and number of stars included in each survey are summarized in Table 4.

4.2.1. NGC 3680 ($l = 286.8°$, $b = 16.9°$)

Kozhurina-Platais et al. (1996) have presented a catalogue of positions, proper motions and photographic B, V magnitudes for 1626 stars in and around the open cluster NGC 3680. The catalogue is complete down to V=16.8 mag in a field of 0.54 square degrees with a bright magnitude limit $V \geq$ 11.0 mag. The photographic V magnitudes are accurate to about 0.1 mag. Kozhurina-Platais et al. (1996) used proper motion data to identify open cluster members, and only 63 cluster members were found. Thus most stars (96%) in their sample are field stars.

Table 3. The main structure parameters in our Galaxy model

Solar Position:	
Distance from the plane	27.5 ± 6.0 pc north[1]
Disk population:	
Luminosity Function	Wielen et al. (1983)
Colour-magnitude diagram	Hipparcos catalogue
Density law	Exponential
Scale length	2250 ± 50 pc[2]
Scale height	a function of $M_{\rm v}$
Thick Disk population:	
Luminosity Function	Wielen et al. (1983)
Colour-magnitude diagram	47 Tuc
Density law	Exponential
Scale length	3250 pc
Scale height	1070 pc
Local normalization	2%
Halo population:	
Luminosity Function	M3
Colour-magnitude diagram	M3
Density law	de Vaucouleurs (1977)
Axial ratio	0.85
Local normalization	0.125%
Extinction Model:	
$A_{\rm v}(r,l,b)$	NCI model

1): This value is determined in this paper; in our previous Galaxy model, this value was assumed to be 0.
2): This value is determined in this paper; in our previous Galaxy model, this value was assumed to be 3250 pc (Bahcall & Soneira 1980).

4.2.2. NGC 1750 ($l = 179°$, $b = -11°$)

Galadí-Enríquez et al. (1998a) have published BVR photographic photometry and astrometric data in a region $2.3° \times 2.3°$ in the area of the open cluster NGC 1750. The main object of that project was to study the overlapping clusters NGC 1750 and NGC 1758. Both clusters are very poor, and the authors only found 158 cluster members in a sample of $R_{\rm limit}$ = 15 mag. Because the view of the field is very large ($2.3° \times 2.3°$), including 11535 stars with a completeness of $V = 17$ mag and a mean precision of 0.08 mag, the contamination of the cluster members is negligible.

4.2.3. Baade’s window ($l = 1°$, $b = -4°$)

Baade’s window data have been obtained by several authors. Paczynski et al. (1994) presented a color-magnitude diagram in the direction of Baade’s window. The observations were made using the 1 m Swope telescope at the Las Campanas Observatory, and a 2048×2048 pixel CCD detector with a pixel size of 0.44 arcsec. Ortolani et al. (1995) have reported ob-

Table 4. Survey characteristics of four low-latitude star count observations

Catalogue	Author	Direction (l, b)	Area coverage deg^2	Limiting mag.	Total sample of stars
NGC 3680	Kozhurina-Platais (1996)	(286.8°, 16.9°)	0.54	$V = 16.8$	1626
NGC 1750	Galadí-Enríquez et al. (1998a)	(179°, -11°)	5.3	$V = 17.0$	11535
Baade's Window	Lindegren (private communication)	(1°, -4°)	1	$I = 21.0$	1.3 10^7
SpA23	Robin et al. (1992)	(179°, 2.5°)	0.0081	$V = 25.0$	930

servations in the region of Baade's Window with the Hubble Space Telescope. Lindegren (private communication) summarized previous observations and gave the star numbers/degree^2 in each magnitude bin in the region of the Baade's window. His results for stars brighter than I = 20 mag were obtained from the Paczynski et al. (1994) data, and for stars fainter than $I = 20$ mag the counts were extrapolated assuming a constant d lg N /d $I \sim 0.5$, as observed between $I = 18$ and 20 mag. Since the contribution of the Galactic bulge may become important for stars fainter than $I = 21$ mag, we limit our discussion to $I < 21$ mag.

4.2.4. SpA23 ($l = 179°$, $b = 2.5°$)

Robin et al. (1992) obtained a deep CCD photometry in the direction of SpA23 ($l = 179°$, $b = 2.5°$). The sample is complete down to $V = 25$ mag in a survey area of 29 arcmin^2. The estimated photometric accuracy in the V band is a function of magnitude from 0.02 mag for $18 < V < 19$ mag to 0.08 mag for $24 < V < 25$ mag.

4.3. Extinction in the studied areas

In Fig. 7, we show the extinction as a function of r in each field from NCI, Hakkila et al. and Sandage extinction models.

For the field of NGC 3680, no specific investigation on the extinction distribution has been presented. The only information we have is the open cluster itself. We have plotted it in Fig. 7a. It can be seen that NCI extinction model is in good agreement with the reddening derived from the open cluster observation.

For the field of NGC 1750, Straižys et al. (1992) derived the interstellar extinction for 116 stars in an area of $2.5° \times 2.5°$ in the direction of the Taurus dark clouds, thus covering the open cluster NGC 1750.

The derived values are included in Fig. 7b together with the foreground absorption derived by Galadí-Enríquez et al. (1998b). We can see a difference of 0.25 mag in extinction between NCI model prediction and that derived from Straižys et al. (1992), which is within the error of NCI model. Moreover, we have changed the extinction law according to the results from Straižys et al. (1992), and found that this difference in extinction does not affect our analysis in the next section.

In the Baade's window, the extinction distribution has been studied by several investigators. Following Arp (1965), Paczynski et al. (1994) found that the absorption increases at about 0.8 to 0.95 mag/kpc for the first 2 kpc, and after 2 kpc, there is no further light absorption. This extinction distribution has also been derived by Ng & Bertelli (1996). We found that NCI extinction model is in good agreement with that found by Arp (1965), Paczynski et al. (1994) and Ng & Bertelli (1996).

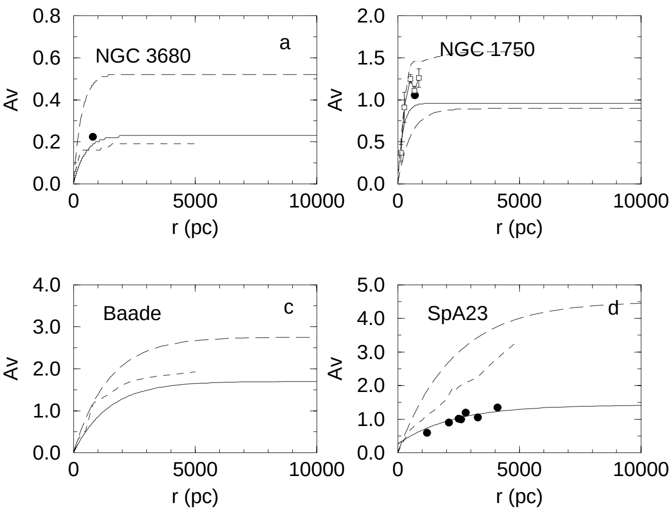

Fig. 7a–d. The extinction in the line of sight in four fields. Solid lines: NCI extinction model, short dashed lines: the Hakkila et al. extinction model, long dashed lines: Sandage's extinction model. The solid circles are the values derived by the authors indicated in Table 2, and the open squares in the field of NGC 1750 are the results from Straižys et al. (1992).

For the field of SpA23, Robin et al. (1992) have investigated the extinction distribution by merging their deep CCD sample and the sample from Schmidt plates. In Fig. 7d, the solid circles are the results derived by Robin et al. (1992). They are in very good agreement with NCI extinction model. Sandage and Hakkila et al. extinction models provide larger extinction values since the resolutions of the studies are not fine enough to identify the low extinction window in this direction.

In summary, we found that NCI extinction model is in full agreement with the observations we have in the four fields studied here. We noticed that Hakkila et al. extinction model drops at r = 5 kpc for all four fields. It is not clear for us if this is for all directions, or only for some directions. In our opinion Hakkila et al. may be unreliable at the distance $r > 5$ kpc.

4.4. Method and results

We compare the simulated catalogues obtained from the Galaxy model including the NCI extinction and the observed ones, in

Table 5. Maximum likelihood values for each data set used in the determination of the scale length h_l and the Solar offset.

Data set	h_l (pc)	Z_{Sun} (pc)
NGC 3680	2250	35
NGC 1750	2375	35
Baade's Window	2125	10
SpA23	2250	30

order to make self-consistency checks in our Galaxy model, and constrain the radial distribution parameters of the galactic disk.

In order to determine the scale length of the disk stars and the solar displacement from the galactic plane, we produce a grid of galaxy models with various disk scale length (h_l) and solar offsets (Z_{Sun}). For each model, we simulate catalogues of data similar to the observed data sets, including photometric errors according to the observations. Then we determine the best-fitting model using a maximum likelihood technique. The likelihood for each model is computed as described in Bienaymé et al. (1987) and Robin et al. (1992):

Let q_i be the number of stars predicted by the model in bin i and f_i be the observed number. Then the probability that f_i be observed is:

$$P_i = \frac{q_i^{f_i}}{f_i!}\exp(-q_i) \tag{9}$$

Then the likelihood of a set of q_i's given the relevant f_i is:

$$L = \Sigma \ln P_i = \Sigma(-q_i + f_i \ln q_i - \ln f_i!) \tag{10}$$

Usually, we use the reduced form to search for the models that maximize L:

$$L - L_o = \Sigma f_i (1 - \frac{q_i}{f_i} + \ln\frac{q_i}{f_i}) \tag{11}$$

where L_o is obtained if $q_i = f_i$ in all bins.

For each observed sample, 130 simulated catalogues have been generated with disk scale length varying between 1500 and 3750 pc and the solar offset Z_{Sun} between -60 pc and 60 pc. The likelihood computation is made in bins with a step of 0.5 mag in V and 0.1 mag in $B-V$ for stars having a $B-V$ measure. Because in the fields of SpA23 and Baade's window, we have no complete colour information, and in the field of NGC 3680, the error in colour is very large, in this study, only for the field of NGC 1750, $B-V$ colour has been used to calculate the likelihood.

In Figs. 8–11, we show the contours of equal likelihood obtained for different values of scale length and the solar offset in the four fields. In general, we found that we cannot determine the scale length of the galactic disk and the solar offset only from one sample. However, by combining the four samples in different galactic directions, we can determine the best-fitting model parameters as explained below:

For the two deep star count samples (SpA 23 and Baade's window), from the maximum of the contours, it can be seen that the maximum likelihood values lie in a region with the scale length between 1750 pc and 2250 pc. From these two samples, we cannot exclude the model with a scale length of 2000 pc and $Z_{Sun} = -40$ pc.

But for the other two samples (NGC 1750 and NGC 3680), it was found that the model with a small scale length (< 2500 pc) and $Z_{Sun} < 0$ definitely cannot fit the data. Thus, from the whole dataset (4 fields together), we can constrain the disk scale length between 2000 pc and 2500 pc and the solar offset between 0 and 40 pc. In order to determine the best-fitting model parameters accurately, we generate, for each observed sample, 100 model simulated catalogues with disk scale length varying between 2000 and 2500 pc and the solar offset between 0 to 40 pc. Each model simulated catalogue was compared with the observed sample, and the best-fitting model is determined by the maximum likelihood technique. In Table 5, we show our best-fitting parameters in each field. Thus, by combining the four samples together, we found that the scale length of the galactic disk h_l = 2250 $\pm$ 50 pc and the displacement of the Sun from the galactic plane Z_{Sun} = 27.5 $\pm$ 6.0 pc.

Most disk density scale length determinations range between 1.8 to 6 kpc (Robin et al. 1992). Ruphy et al. (1996), Durand et al. (1996) and Porcel et al. (1998) found a scale length of 2.5 kpc, 2.3 kpc and 2.1 kpc for disk stars from COBE maps, DENIS survey and Two Micron Galactic survey, respectively. Kent et al. (1991), Ng et al. (1995) and Lewis & Freeman (1989) found a value of h_l in the range 3.0 to 4.5 kpc. Méndez & van Altena (1998) and van der Kruit (1986) obtained a larger value of 6.0 kpc and 5.5 kpc from the Guide Star Catalogue (Lasker et al. 1990) and the *Pioneer* 10 background experiment, respectively. Our results agree with the determination by Bienaymé & Séchaud (1997), who favoured a small scale length in the range 1.7–2.9 kpc from an analysis of the kinematics of neighbouring stars. Our results are also in good agreement with that (2.5 kpc) derived by Robin et al. (1992) from their SpA 23 star count observation. This is interesting, because our Galaxy model is different from Robin et al. (1996) Galaxy model, on its construction and model parameters. Both analysis derive the same results, indicating that the results are not sensitive to other model parameters adopted in the Galaxy model.

Another important parameter in the Galaxy model is the solar offset from the galactic plane. The value of Z_{Sun} has an impact not only on the predicted reddening but also on the density distribution of the different types of stars when looking at the Galactic plane at positions slightly above or below it (Méndez & van Altena 1998). The asymmetry in the distribution between the NGP and SGP has been ascribed to the solar position in the plane. The general trend is that an offset, ranging from 5–40 pc, north of the galactic plane has been found (Ng et al. 1997). Stothers and Frogel (1974) determined Z_{Sun} = 24 $\pm$ 3 pc from B0-B5 stars within 200 pc of the Sun, Pandey et al. (1988) obtained 28 $\pm$ 5 pc from an examination of the distribution of open clusters, Conti and Vacca (1990) found 15 $\pm$ 3 pc from a sample of 101 Wolf-Rayet stars, same result (15.5 $\pm$ 3 pc) has been found by Hammersley et al. (1995) from COBE, IRAS and the Two-micron galactic survey (TMGS). Méndez & van Altena (1998) derived 27 $\pm$ 3 pc from a comparison between

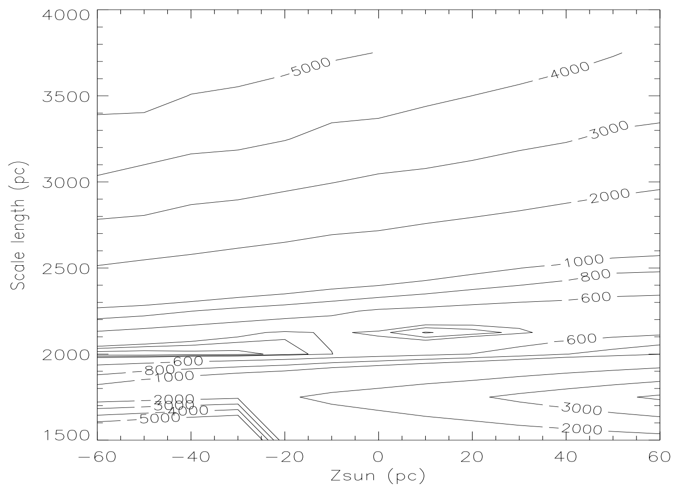

Fig. 8. The contours of equal likelihood obtained for different values of disk scale length and the solar offset in the field of Baade's Window.

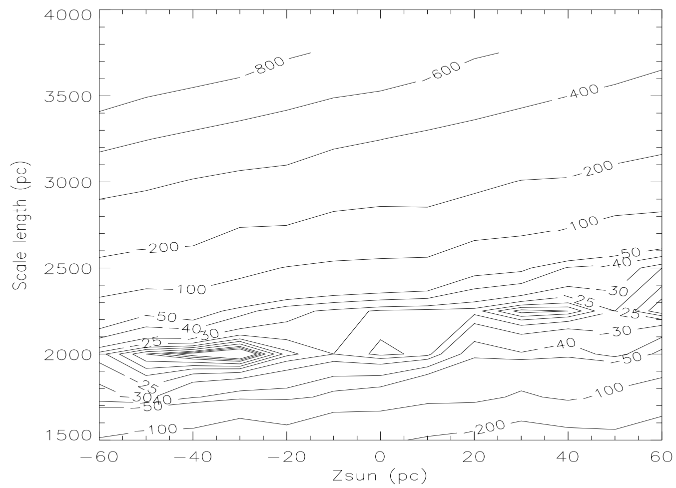

Fig. 10. The contours of equal likelihood obtained for different values of disk scale length and the solar offset in the field of SpA 23.

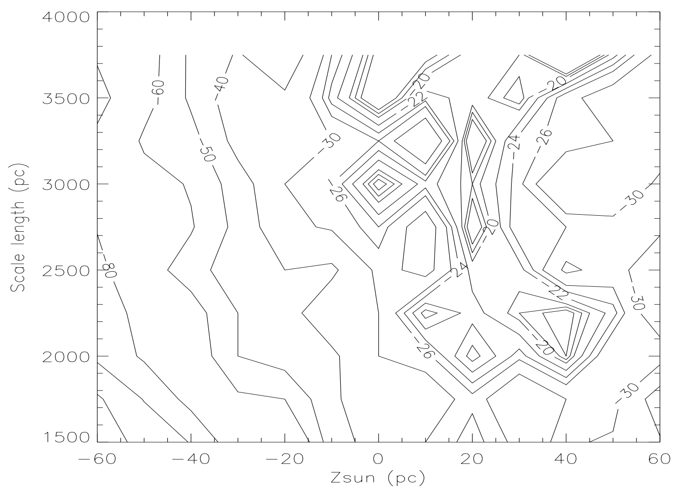

Fig. 9. The contours of equal likelihood obtained for different values of disk scale length and the solar offset in the field of NGC 3680.

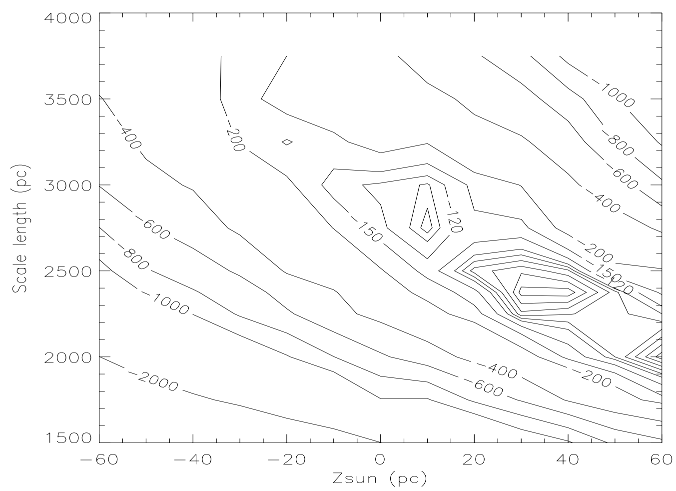

Fig. 11. The contours of equal likelihood obtained for different values of disk scale length and the solar offset in the field of NGC 1750.

model simulations and the Guide Star Catalogue. Binney et al. (1997) derived a value of $Z_{\rm Sun}$ = 14 pc above the plane from a dust-corrected near-infrared COBE/DIRBE surface brightness map of the inner Galaxy. Our result is consistent with almost all results above in two sigma levels.

5. Conclusions

The objective of this investigation is to extend our Galactic structure and kinematic model to the low-galactic latitude, which has been achieved by introducing a new large-scale extinction model in our Galaxy model software. Then we compare the simulated catalogues and the observed ones and make a self-consistency checks in our Galaxy model in order to constrain the radial scale length of the galactic disk and the Sun's position above the plane.

We have tested the SFD all-sky reddening map by globular cluster database, and we found that this new reddening map has an accuracy of 18%, but overestimates visual absorption by a factor of 1.16. This result has been confirmed from our open cluster dataset and a direct comparison between the SFD reddening map with the Burstein & Heiles map. We have proposed a large-scale 3-dimensional extinction distribution (NCI extinction model), considering that the Sun may be out of the galactic midplane. We demonstrated that this model is twice as accurate as the previous large-scale extinction models (Sandage 1972; Hakkila et al. 1997).

Four star-count samples at low-galactic latitude have been used to compare with galactic model simulations. The best-fitting model is determined by using a maximum likelihood method. We found that, for a given galactic direction, there are several local maximum values from the maximum likelihood technique, indicating that it is impossible to provide a unique solution for the scale length of the galactic disk and the solar offset from the galactic plane. However, analyzing simultaneously four samples at different galactic directions, we can determine the best-fitting model parameters. We found the scale length of the galactic disk h_l = 2250 $\pm$ 50 pc and the displacement of the Sun above the galactic plane $Z_{\rm Sun}$ = 27.5 $\pm$ 6.0 pc.

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