THE STRUCTURE OF THE THICK DISC

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ABSTRACT

The existence of the thick disc is now well established, although its spatial, chemical and kinematic properties are not clearly defined. As stressed by several authors, observations towards multiple directions are needed in order to resolve the correlations between the various model parameters. Here, we present a new survey over about 140 square degrees based on the material used for the construction of the Second Guide Star Catalog (GSC-II). A sample of about 20 000 K dwarfs up to 3 kpc selected from multiple fields towards high and intermediate latitudes has been analysed in order to trace the spatial distribution of the thick disc. Photometric parallaxes (30% accuracy) have been computed taking into account the systematics effects due to the Malmquist bias, the Eddington bias, the metallicity gradients, and the contamination of giants and binaries. A least-squares analysis of the seven fields supports a thick disc with a vertical scale-height, $h_z \simeq 1.0$ kpc and a relative density of about 5% and a radial scale-length $h_R \simeq 3.2$ kpc, and a thin disc with $h_z \simeq 240$ pc. Finally, the impact of the accurate astrometric measurements, including absolute parallaxes, expected from Gaia is discussed.

Key words: Galaxy: structure, disc; Surveys; Methods: statistical.

1. INTRODUCTION

The thick disc corresponds to the Intermediate Pop. II (Gilmore & Reid 1983), whose existence is now well established, although its properties are not clearly defined. For instance, scale-height estimations range from 640 pc (Du et al. 2003) to 1500 pc (Reid & Majewski 1993). Intermediate values include 800 pc by Reylé & Robin (2001), 900 pc by Larsen & Humphreys (2003), 1 kpc by Ng et al. (1997) and 1100 pc by Spagna et al. (1996). As stressed by several authors, observations in many different directions are needed in order to resolve the correlations between the various model parameters.

Here, we present a new survey including 7 GSC-II fields (Table 1) covering an area of about 140 square degrees

Table 1. Plate material. Centres of the POSS-II fields used for this study.

Field	POSS-II	l	b
NGP 2	443	77.31°	+86.11°
NGP 3	444	54.33°	+81.95°
NGP 4	381	125.36°	+82.33°
AC	261	175.49°	+45.10°
GC	864	329.17°	+60.01°
GR 1	893	81.34°	−55.21°
GR 3	824	107.49°	−61.69°

towards the North Galactic Pole (NGP) and intermediate latitudes in the direction of the galactic centre (GC), anticentre (AC) and galactic rotation (GR).

Our material consists of blue B_J, red R_F and infrared I_N POSS-II Schmidt plates digitized at STScI with modified PDS-type scanning machines (15 μm/pixel, i.e., $1''$/pixel) and initially analyzed by means of the standard software pipeline used for the construction of the GSC-II (McLean et al. 2000). The pipeline performs object detection and computes parameters and features for each identified object. Further, the pipeline software estimates classification, position, and magnitude for each object by means of astrometric and photometric calibrations using the Tycho-2 (Høg et al 2000) and the GSPC-2 (Bucciarelli et al. 2001) as reference catalogues. Accuracy better than 0.1–0.2 arcsec and 0.1–0.2 mag are generally attained by GSC-II calibrations.

These data have been analysed by means of a complete sample of stellar tracers for which photometric distances have been estimated (Section 2) taking into account various the type of systematic effects (Section 3). Then, the spatial distribution of the parent populations have been derived directly from the tracer counts (Section 4). The alternative and potentially more general approach is to fit the spatial distribution and other astrophysical properties (e.g., luminosity function, IMF, star formation rate, chemical abundance distribution, ...) through a comprehensive Galaxy model used to predict the observed star counts as a function of colour and magnitude. In the first case, the spatial distribution comes simply from the tracer distances, for which – however – a detailed error model is required due to non-linear error propagation and to the presence of possible astrophysical and observation

biases. In the second case, the error model is straightforward, as star counts predicted by a Galaxy model are naturally compared to the observed counts affected by measurement errors and poissonian statistics only. On the other hand, a more complex machinery described by a larger number of degrees of freedom (partially reduced by astrophysical constraints) is necessary to define a consistent Galaxy model.

2. PHOTOMETRIC DISTANCES

For each field we extracted stellar objects from the unvignetted area within $2.5°$ of the plate centres and selected photometrically a sample of about 20 000 K dwarfs ($6 < M_F < 7$) on the basis of their colour indexes, $B_J - R_F$, as tracers to study *in situ* the spatial structure of the thin and thick disc up to a distance of 3 kpc.

Photometric parallaxes (30% accuracy) have been estimated by means of colour-to-absolute magnitude relations (CMR), based on Padova theoretical isochrones (Girardi et al. 2000) transformed to the GSC-II photometric system, $B_J R_F$, using the colour transformations adopted for the photometric calibration of GSC-II.
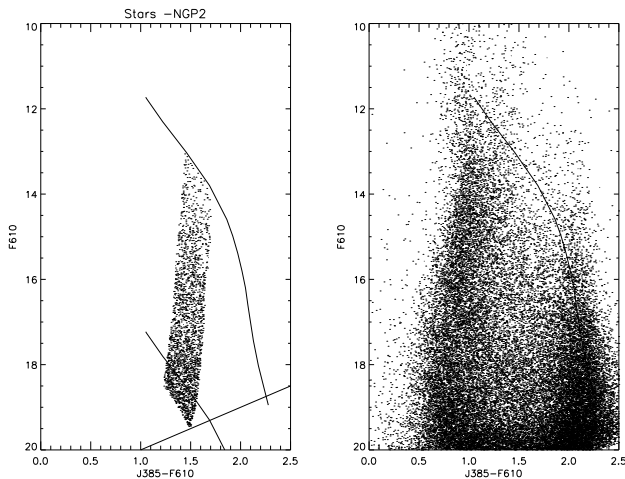

Figure 1. Left panel: CMD R_F vs. $B_J - R_F$ of the selected tracers ($6 \leq M_F \leq 7$) in field NGP2. The upper and lower curves indicates the main sequence (based on isochrones with $Z = Z_\odot$) located at m–M = 7.0 ($d \simeq 250$ pc) and m–M = 12.5 ($d \simeq 3160$ pc), respectively. Right panel: CMD R_F vs. $B_J - R_F$ of all the stellar objects in field NGP2.

The precision of photometric parallaxes is related to various terms that contribute to the distance modulus error:

$$\sigma^2_{R_F - M_F} = \sigma^2_{R_F} + \left[\frac{dM_F}{d(B_J - R_F)} \right]^2 \sigma^2_{B_J - R_F} + \sigma^2_M \quad (1)$$

that depends (1) on the photometric observation errors, $\sigma_{R_F} \simeq \sigma_{B_J} \simeq 0.1$, (2) the slope of the colour-absolute magnitude relation, $d(M_F)/d(B_J - R_F)$, and (3) the intrinsic dispersion of the CMR, for which we adopted $\sigma_M \simeq 0.3$, close to the value derived by Upgren et al.

(1997) for the old disc population on the basis of a maximum likelihood analysis of a sample of K and M dwarfs within 50 pc.

In our case, these terms lead to a distance modulus error $\sigma_{(R_F - M_F)} \simeq 0.6$ mag, i.e., a distance precision of about $\sigma_d/d \simeq 30\%$.

3. CORRECTION FOR SYSTEMATIC EFFECTS

Lacking trigonometric parallaxes, photometric surveys are affected by various effects that may introduce systematic errors to the individual photometric distances and to the total spatial distribution. The following cases have been taken into account and statistically corrected.

INTERSTELLAR EXTINCTION. Although in our fields extinction is not critical ($E_{(B-V)} \simeq 0.05$ mag in the worse case), the observed magnitudes, B_J and R_F of each star have been corrected by means of an extinction model based on the dust distribution ($\propto \sinh^2(z/h_d)$ derived by FIR observations (Drimmel & Spergel 2001), normalized to the galactic extinction maps published by Schlegel et al. (1998).

UNRESOLVED BINARIES. The presence of a certain fraction of unresolved binaries introduces a systematic bias in the evaluation of the photometric distances, which will typically be underestimated by the M_F vs. $B_J - R_F$ calibration which is strictly valid for single stars only. This effect has been corrected adopting a 'system' CMR providing the mean absolute magnitude as a function of the mean colour of the binary system, assuming a fraction of 50% unresolved binaries with uniform mass ratio distribution, i.e., f(q) = const, where $q = m_2/m_1$.

STELLAR METALLICITY. Individual absolute magnitudes, M_F, were computed as a function of the colour $B_J - R_F$, by means of a linear interpolation through a set of isochrones ($Z = 0.019$, 0.004 and 0.0004), after assuming a mean metallicity for each star as a function of the distance z from the galactic plane, adopting a vertical metallicity gradient, [Fe/H]=$f(z)$, from Yoss et al. (1987).

GIANT CONTAMINATION. Although the spatial density of evolved stars is much smaller than that of main sequence stars, the relative fraction of giants at a given apparent magnitude may increase because they are sampled within a bigger volume at a larger distance. However, this effect is reduced or compensated towards lines of sight where the stellar density is decreasing with the distance, such as for our fields. In the following analysis the contamination of evolved stars is neglected.

MALMQUIST BIAS. Because our tracers are selected from a magnitude limited survey they appear systematically *brighter* than objects sampled from an unbiased volume limited survey, by a factor:

$$\langle M \rangle_m - M_0 = -\sigma^2_M \frac{d \ln A(m)}{dm} = -\ln 10 \cdot \sigma^2_M \cdot \alpha \quad (2)$$

where $A(m) \propto 10^{\alpha \cdot m}$ is the distribution of the differential star counts as a function of the apparent magnitude m. The exponent $\alpha = \alpha(m)$ which depends on the luminosity function and space density via the fundamental equation of the stellar statistics has been derived from the observed star counts to correct the photometric parallaxes. The 'cosmic' scatter, σ_M, depends on the metallicity and age distribution, contamination of unresolved binaries, etc. Here, an intrinsic dispersion $\sigma_M = 0.30$ mag (Upgren et al. 1997) has been adopted.

EDDINGTON BIAS. The observed distance-modulus distribution of the tracers, $N_{\text{obs}}(m - M)$, from which their spatial distribution is derived, is slightly distorted with respect to the true distribution, N_{true}, due to the convolution with the uncertainty on the distance modulus, $\sigma_{R_F - M_F}$, given in Equation 1. An approximate correction has been applied by means of the approximate Eddington series (Trumpler & Weaver 1953):

$$N_{\text{true}} \simeq N_{\text{obs}} - \frac{\sigma_{m-M}^2}{2} N_{\text{obs}}'' \qquad (3)$$

4. SPATIAL DISTRIBUTION

The distribution of the stellar tracers as a function of the distance depends on the actual volume and on the local space density $\rho(r)$:

$$dN = \frac{\Omega}{3} \rho(r) \, r^2 \, dr \qquad (4)$$

where $r = 10^{0.2(m-M)+1}$ and $\rho(r)$ is the spatial density that we assume does not vary significantly over the solid angle Ω of the field of view.

Our tracers ($M_F = 6$–7) have been selected with distance moduli between $7 < m - M < 12.5$ and reach a distance from the plane $|z|_{\text{Max}} \simeq 2.5$ and 3 kpc for the intermediate and high latitude fields, respectively. Within this volume the thin and thick disc populations are dominant with respect to the halo, so that we consider a spatial density distribution as a sum of the two disc distributions, $\rho = \rho_{\text{thin}} + \rho_{\text{thick}}$, each described by an axisymmetric double exponential function characterized by a vertical scale height, h_z and a radial scale length, h_R, as follows:

$$\rho(R,z) = \rho_0 \, \exp\left(-(R - R_{\odot})/h_R\right) \, \exp\left(-|z|/h_z\right) \qquad (5)$$

where the galactocentric cylindrical coordinates, (R, z), are defined as $z = r \sin b + z_{\odot}$ and $R^2 = (r \cos)^2 + R_{\odot}^2 - 2r \, R_{\odot} \cos l \cos b$. We assumed the Sun's location to be at $z_{\odot} = 15$ pc and $R_{\odot} = 8$ kpc. Moreover, the scale-length of the thin disc, to which our fields are not sensitive, was set to $h_R \simeq 3.0$ kpc.

Taking into account all the systematic effects listed in Section 3, we derived a global least squares solution on all the seven fields whose results, reported in Table 2, support a thick disc with a vertical scale-height, $h_z \simeq 1000$ pc, a local relative density of about 5% at $z = 0$, a radial scale-length $h_R \simeq 3.2$ kpc, and a thin disc with $h_z \simeq 240$pc. With respect to the previous studies, these values are consistent with authors who claim
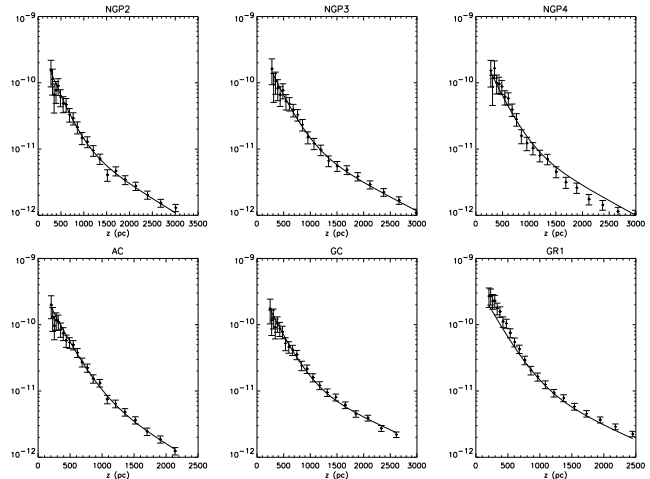

Figure 2. Observed density in 6 fields as a function of the height z compared against the model based on the multi-field best-fit solution (solid line). Poissonian error bars ($\pm 2\sigma$) are also indicated for the observed densities.

a thick disc characterized by intermediate scale-heights (e.g., Ng et al. 1997, Ojha 2001; Siegel et al. 2002; Larsen & Humphreys 2003) and a relatively short scale-length (≈ 3 kpc) similar to that found by Robin et al. (1996), Buser et al. (1999), Siegel et al. (2002).

In Figure 2 the observed vertical density of tracers is compared against the model prediction for 6 fields. The agreement is quite good, even though some systematic differences are noticeable in a few cases at the bright or faint end, possibly due to the presence of non-axisymmetric structures or also to systematic errors affecting the photometric data.

5. DISCUSSION

A new multi-field magnitude limited survey at high and intermediate latitudes based on the material used for the construction of GSC-II has been presented and used to investigate the spatial distribution of the thick disc. Photometric parallaxes (30% accuracy) have been computed for about 20 000 K dwarfs by means of theoretical CMR, from Girardi et al. (2000) and taking into account the systematic effects due to Malmquist bias, Eddington bias, metallicity gradients, and contamination from giants and binaries.

The most significant term is given by the correction for the *mean* vertical metallicity gradient that affect the estimation of the distance moduli of our most distant stars up to ~ 0.5 mag. It is evident that in this case the availability of spectro-photometric chemical abundances for the individual tracers would have provided a more accurate correction.

The presence of unresolved binaries is also a critical point as it may introduce distance modulus errors up to 0.753 mag in the case of binaries with equal mass com-

Table 2. Spatial parameters of the thin and thick disc estimated from the multi-field best-fit assuming a binary fraction $f = 0\%$ or 50% with an uniform mass ratio distribution, $f(q)$ =const. Formal random errors and reduced χ^2 from the fit are also provided.

Binary fraction	h_z thin (pc)	h_z thick (pc)	h_R thick (kpc)	$\rho_{\text{thick}}/\rho_{\text{thin}}$	χ^2/ν
0%	230 ± 5	965 ± 28	2.98 ± 0.12	0.047	2.778
50%	242 ± 6	1022 ± 34	3.20 ± 0.13	0.050	2.600

ponents. On average, the $m - M$ mean correction decreases to ~ 0.2 mag, assuming a population of binaries with uniform mass ratio distribution.

Although non-negligible, the systematic effects introduced by the Malmquist and Eddington biases, due to 'cosmic' dispersion and photometric errors respectively, are much smaller than those mentioned previously. In particular, the Malmquist bias in our fields is typically of a few hundredths of magnitude and in the worse cases it does not exceed $\Delta M \simeq 0.1$ mag.

Clearly, all these problems affecting photometric parallaxes will be dramatically reduced by a deep and complete survey of accurate trigonometric parallaxes as expected from the Gaia mission. In fact, direct distances for complete volume limited samples will be available from absolute parallaxes that do not depend on theoretical or empirical CMR and are much less sensitive to the presence of unresolved binaries. Nevertheless, also in this case the accurate knowledge of the error model of the astrometric parameters will be necessary to correct properly any statistical effect (eg., Lutz-Kelker bias) that may affect the analysis of large stellar samples.

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