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The thick disc of the Galaxy: sequel of a merging event

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Abstract. Accurate characterization of thick disc properties from recent kinematic and photometric surveys provides converging evidences that this intermediate population is a sequel of the violent heating of early disc populations by a merging satellite galaxy.

The thick disc population is revisited under the light of new data in a number of galactic sample fields. Various thick disc hypotheses are fitted to observational data through a maximum likelihood technique. The resulting characteristics of the thick disc are the following: a scale height of 760 ± 50 pc, with a local density of 5.6 ± 1 % of the thin disc. The scale length is constrained to be 2.8 ± 0.8 kpc, well in agreement with the disc scale length (2.5 ± 0.3 kpc). The mean metallicity of the thick disc is found to be -0.7 ± 0.2 dex, with no significant metallicity gradients.

These photometric constraints in combination with kinematic data give new constraints on the thick disc formation. We show that thick disc characteristics are hardly compatible with a top-down formation scenario but fully compatible with a violent merging event arising at the early thin disc life time as described by Quinn, Hernquist & Fullagar (1993).

Key words: Galaxy: stellar content – Galaxy: evolution; formation – Galaxy: structure

1. Introduction

After a decade-long controversy about the existence or non-existence of a thick disc in the Galaxy, data accumulate to support the existence of such a component. Many observations show that this population is distinct from the disc and the halo (see Reid & Majewski 1993, hereafter RM, for a review). However the formation of this component is still an open question. In the absence of a complete description of the population, it is almost impossible to design a probable scenario. Yet understanding this population is a necessary step towards understanding the galaxy formation, halo collapse, disc collapse and disc dynamical and chemical evolution.

The reason why the characteristics remain controversial is related to the fact that its members cannot be easily recognized from the disc or the halo members in most observable distributions, such as magnitude - colour diagrams, or even in reduced proper motion diagrams, specially if the photometry is not accurate enough. More discriminating data, like metallicity and radial velocity distributions, hardly constrain the scenario because they generally concern a too small number of stars on a small area of the sky. The determination of the thick disc structural parameters requires large star samples in various directions well distributed in longitude and latitude. As a result the density law, the local density and the metallicity of the thick disc still remain uncertain.

While it is generally assumed that the density law can be modelled by a double exponential, the scale length is unknown and scale height measurements range run between 700 pc (Yamagata & Yoshii 1992) and 1500 pc (Reid & Majewski 1993, see this reference for a review of recent determinations). In most galactic models the estimated thick disc scale height seems to be correlated with the assumed disc scale height, since in B-V counts the two populations are not well separated. U-B colour distributions give a better separation between the two populations due to blanketing effect, but they are scarcely available due to the difficulty of getting good calibrations in the U band.

The local density of this population has hardly been measured directly in the solar neighbourhood. Several attempts have been made using high proper motion stars (Sandage & Fouts 1987a; Casertano et al. 1990). They do not give an accurate measurement ($\rho_0 > 2\%$ for the former, 10 ± 5 % for the latter). This method is more reliable for halo stars because they are easily distinguished from disc stars by their kinematics.

The local density of the intermediate population can be deduced from remote star counts but such estimates are correlated with the scale height. Large local density estimates are obtained in combination with short scale height, while small local density are associated with large scale heights (e.g. RM found 2.0-2.5 % with a scale height of 1400 pc). Estimates range between 1% of the disc density to more than 10%. RM argue from the

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analysis of their own data towards the North Galactic Pole that the thick disc scale height cannot be measured independently from its local normalization. However combining data at different latitudes and longitudes this apparent degeneracy can be removed.

The metallicity distribution of the thick disc has never been accurately measured because of the lack of complete samples of thick disc stars free from observational bias. It is generally admitted that its mean metallicity is compatible with the one of the disc globular clusters (-0.6 to -0.7) but could extend from -0.5 (the supposed limit for the old disc) to -1.5 (Morrison et al. 1990).

Most investigations based on photometric star counts try to derive thick disc characteristics through direct inference from data in one field. As a result, since broad band photometry is not sufficient to unambiguously discriminate thick disc stars from halo and thin disc ones, estimates of the properties of this component are biased by population confusion. In contrast in a fully synthetic approach fitting model predictions to data in many fields, the discrimination is based on the characteristics of observed distributions. Then model components are resolved under strict control.

The Besançon model of stellar population synthesis has been developed in order to study the galactic structure and to understand the formation and evolution of the Galaxy (Robin & Crézé 1986; Bienaymé et al. 1987; Haywood 1994). In parallel to this approach, an observational programme has been started in collaboration between the french observatories of Besançon, Strasbourg, Paris and the Uttar Pradesh State Observatory, featuring photometric and proper motion star counts in several directions. These data combine Schmidt plate UBV photometry and proper motions up to magnitude 18 or 19 in V and complementary deep CCD data in few sub-fields. A description of the programme may be found in Robin et al. (1993)

In this paper we describe an attempt to solve for the main characteristics of the thick disc population (scale height, scale length, local density, metallicity) using photometric star counts in a number of directions and the model of population synthesis. We present in Sect. 2 the data set used in this analysis. In Sect. 3 we describe the characteristics of the model simulated data. The statistical tests applied to photometric data to obtain the structural parameters of the thick disc are described in Sects. 4 and 5. Implications for the thick disc nature and origin, in combination with other kinematic data, are discussed in Sect. 6.

2. Star counts

In addition to data from our own survey, star count data from a number of other investigations have been compiled and entered in the global match. However the investigation has been limited to data sets including at least the V and B band.

2.1. Photometric catalogues

The Besançon photometric and astrometric sample survey supplies photometric data samples with an accuracy better than 0.1 magnitude in UBV in 5 fields. Among those, here we use the fields at intermediate latitude on the galactic meridian and one field toward the galactic pole:

- A field near the globular cluster M 5 (l=2.7°, b=47.4°) (Bienaymé et al. 1992; Ojha et al. 1994b, hereafter called "Galactic Center Intermediate Latitude" GCIL) which covers 15.5 square degrees and is complete to 18 in V, 19 in B and 18 in U.
- A 7.13 square degree field at l=167.5° and b=47.4° (Ojha et al. 1994a) complete to 18.5 in V, 20 in B. We call it Anticentre Intermediate Latitude, ACIL.
- A field close to the north galactic pole, near the globular cluster M 3 (Soubiran 1992) (l=50°, b=80°) covering 20.26 square degrees and complete to about 17.5
- A field in the direction of antirotation at intermediate latitude (l=277.8°, b=46.7°) covering 20.84 square degrees and complete to 18.5 in V, 20 in B, 18.5 in U.

Other star counts surveys suitable for our analysis include:

- Chiu's (1980) survey in three selected areas (SA57 near the north galactic pole, SA68 (l=111 °, b=-46 °), SA51 (l=189°, b=21°). Each field covers 0.1 square degree and reaches magnitude 20 in V and 21 in B.
- The Gilmore et al. (1985) survey concern two fields: the SGP on 11.5 square degrees and a field in Aquarius (l=37°, b=-51°) on 18 square degrees. Both fields are complete to about 18 in B and V.
- The Basle Halo Programme (hereafter BHP) contains a number of fields in three colour photometry on small areas of sky, of the order of 1 to 2 square degrees. Most of them are in the RGU system and require a conversion to the Johnson system. Few fields of the BHP are also available in UBV: SA57 by Fenkart & Esin-Yilmaz (1985) and Spaenhauer (1989 and private communication), and SA54 (l=179°, b=51°) by Fenkart & Esin-Yilmaz (1983) and are used in the present study.
- Stobie & Ishida (1987) produced UBV star counts towards the NGP from Schmidt plates on 21.46 square degrees. The data are complete to about 18 in V.
- Yamagata & Yoshii (1992) field is in SA54 (l=200°, b=59°). It is complete up to magnitude 18 in V.
- Ratnatunga (1984) explored 3 fields (SA127 (l=272°, b=-38.6°), SA141 near the south galactic pole, SA189 (l=277°, b=-50°) in a photometric and spectroscopic survey between 9 and 14 in V on areas of about 20 square degrees.
- Friel & Cudworth (1986) observed two fields in a photometric and spectroscopic survey: Serpens (l=37°, b=+51°) and SA94 (l=175°, b=-49°). Their BV sample is limited to 14 in V and covers only 4 square degrees.
- Deeper counts have been obtained on smaller areas from prime focus plates in J and F between magnitude 20 and 22. Kron (1980) and Koo & Kron (1982) observed SA57 and

SA68 on 0.1 square degree. At very faint magnitudes the star-galaxy separation is doubtful on photographic plates. Trevese & Kron (1988) looked for variabilities in the same field in several colours (U,J,F,N) and verified the star-galaxy separation from the Koo & Kron sample. The resulting sample is probably free from extragalactic objects.

- Majewski (1992) obtained new star counts in SA57 from prime focus plates in several colours and proper motions. He surveyed an area of about 0.3 square degree and is complete to V=22.5.

2.2. Data accuracy

When comparing colour distributions in neighbouring fields from different authors, star density discrepancies are sometimes larger than the Poisson noise and larger than photometric random errors, as estimated by the authors. In Fig. 1 we compare B-V histograms from these wide field surveys in the polar caps (SI, GRH and Soubiran). Disagreements appear well before the limiting magnitude and specially in the wings of the distributions. In U-B the problem is even more acute. Figure 2 shows U-B histograms in different V magnitude bins at the pole from different authors. There is no discrepancies between Spaenhauer and Fenkart & Esin-Yilmaz data but Stobie & Ishida data appear systematically shifted by 0.1 to 0.2 magnitudes. The same problem appears between Fenkart & Esin-Yilmaz and Yamagata & Yoshii colour distribution towards SA54. The discrepancies could be due to true differences from field to field. This would be a signature of local inhomogeneities of the Galaxy. If these differences are real we should use a mean of these distributions so as to get the mean properties of the populations. However, the existence, in some cases, of a disagreement appearing only in U-B and not in B-V indicates that it is most likely a problem of photometric systematic errors. It is well known that calibration of Schmidt plates leads easily to systematic errors if standard stars are too scarce, or not well distributed in magnitude and in position over the plate. This is often the case in the U band and the non-linearity of the calibration leads to systematic deviations at magnitudes at which no standards are available. It should be noted that Spaenhauer and Fenkart & Esin-Yilmaz use the same plate-emulsion combination and the same scanning machine. They obtain the same realization of the UBV system, while this is not the case for the other data sets. As a conclusion, one need to take into account, in the analysis, star count errors larger than the Poisson noise. Discrepancies as large as 0.1 mag. in U-B can be observed between two different implementations of the same photometric system. Furthermore while each group claims reliability and completeness of their photometry down to magnitude 18, obvious discrepancies cast doubt on any interpretation beyond $m_V = 17$.

3. Modelling aspects

The Besançon model of stellar population synthesis has been developed for about 10 years as an attempt to put together all constraints (theoretical and observational) about galactic evolution in order to obtain a consistent scenario of galaxy evolution. The steps of this approach have been the following: Robin & Crézé (1986) built a population synthesis model using an evolutionary scheme from Rocca-Volmerange et al. (1981) suitable for external disc galaxies. Bienaymé et al. (1987) used dynamical constraints (Boltzmann and Poisson equations and the observed rotation curve) to determine the scale heights of the disc, according to the potential of a self-consistent mass model. The kinematical parameters are function of age (Robin & Oblak 1989). Then, in order to investigate the Initial Mass Function and the Star Formation history in the galactic disc, Haywood (1994) improved the evolution computation using the most recent evolutionary tracks and obtained strong constraints on the slope of the IMF, the history of the SFR in the past and on the age-vertical velocity dispersion relation, i.e. on the process of orbit diffusion in the disc. The model we use in this analysis is the best fit model determined by Haywood (1994). The evolution of the disc is described by a constant star formation rate, an age-velocity dispersion relation rising to 21 km s^{-1} for oldest disc stars and a three-slope Initial Mass Function. Evolutionary

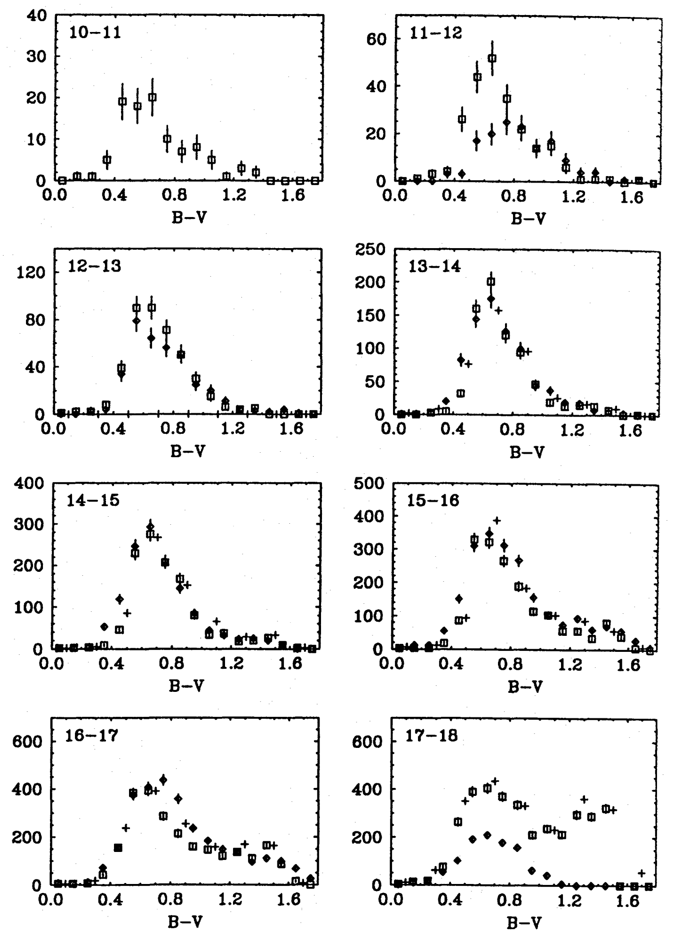

Fig. 1. B-V distribution towards galactic poles in V magnitude bins from Stobie & Ishida (1987, squares), Soubiran (1992, diamonds) and Gilmore et al. (1985, crosses). Error bars are 1 sigma Poisson noise

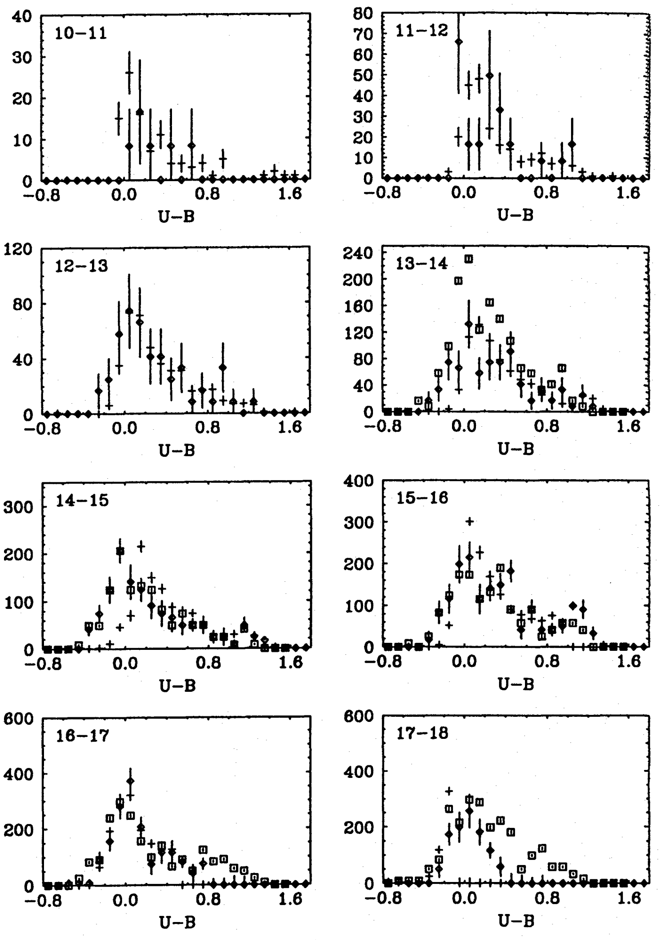

Fig. 2. U-B distribution towards galactic poles in V magnitude bins from Stobie & Ishida (1987, crosses), Fenkart & Esin-Yilmaz (1985, squares), Spaenhauer (1989, diamonds). Error bars are 1 sigma Poisson noise

tracks are from Schaller et al. (1992) and Vandenberg (private communication).

The model, initially limited to UBV photometry, has been extended to red and near infrared bands (R I J H K L), (Robin 1993) and to IRAS 12 microns and 25 microns bands (Guglielmo & Robin 1993).

Thin disc metallicities are a function of age, following Twarog (1980). A natural metallicity dispersion at each age ranging from 0.12 dex at 1 Gyr to 0.20 dex at 10 Gyr. The oldest thin disc stars have metallicities of -0.37 $\pm$ 0.2. Since old stars have also larger scale heights than young ones, this creates a vertical metallicity gradient in the disc of about -0.15 dex kpc^{-1} in the case of our metallicity-age-scale height relation. This vertical disc gradient is not a free parameter in the model. It is given by the age-metallicity and age-scale height relations. More recent age-metallicity relation (AMR) from Edvarsson et al. (1993) give a slightly higher metallicity for old disc stars and a smaller age-metallicity dependence. They find a mean metallicity of -0.25 dex for disc stars older than 6.3 Gyr at the solar position. But according to the large dispersion in metallicity for a given age (about 0.2 dex) they also claim that their AMR is consistent with Twarog (1980) and Meusinger et al. (1991). Actually the results of the present paper on the thick disc characteristics do not depend on the assumed AMR for the disc because colour bins used in the model fitting are widely dominated by the thick disc population.

The blanketing vector calculations have been computed using the model atmospheres from Buser & Kurucz (1992). Since the blanketing correction is a non-linear function of the metallicity, even for small metal deficiencies, we compute for each luminosity class a blanketing correction in U-B and B-V as a polynomial function of [Fe/H] and B-V. These functions were computed in the domain where the atmosphere models are available, that is from spectral types F to K. For later type stars we extrapolated, assuming that the blanketing effect becomes negligible for red dwarfs at about B-V=1.5, as can be seen in models from Bergbush & Vandenberg (1992). No U-B star counts are presently available for metal poor M dwarfs in order to check this assumption. For early type stars with B-V < 0.1 the blanketing correction is supposed to be 0. For $0.1 <$ B-V < 0.54 (for which reliable atmosphere models are not available) we interpolate the blanketing between the values at 0. and 0.54. This has no effect on this study where late populations dominate.

For thick disc and halo populations we adopt the M_V vs B-V relation given by Bergbush & Vandenberg (1992) and we apply the Buser & Kurucz models to compute the U-B colours for a set of 4 metallicities (-0.65, -1.3, -1.6 and -2.2). Intermediate metallicity models are obtained by linear interpolation. Figure 3 shows the resulting colour-colour diagrams at different metallicities. The thick disc and halo luminosity functions are those of 47 Tuc and M 3 respectively.

4. Fitting method

4.1. Maximum likelihood

In order to determine the structural parameters of the thick disc, we produce a grid of thick disc models, with different values of the local density, scale height and scale length. For each thick disc model we simulate catalogues of data similar to the observed data sets, including photometric errors according to the authors. For a better statistics and to minimize the Poisson noise in model simulations, small field catalogues (areas smaller than 5 square degrees) are simulated ten times. Then we compute the likelihood of the observed catalogues to be a realization of each model. The likelihood is computed as described in Bienaymé et al. (1987, appendix C):

Let q_i be the number of stars predicted by the model in bin i and f_i be the observed number. In case the deviations of f_i's with respect to q_i just reflect random fluctuations in the counts, each f_i would be a Poisson variate with mean q_i. Then the probability that f_i be observed is:

$$dP_i = \frac{q_i^{f_i}}{f_i!} exp(-q_i) \quad (1)$$

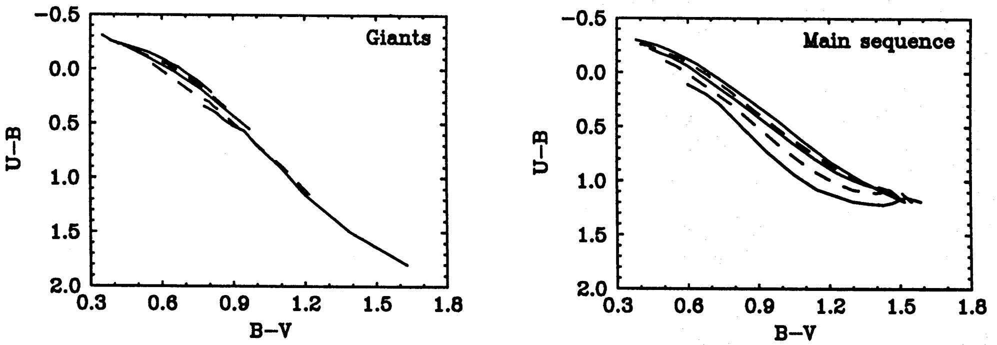

Fig. 3. (U-B,B-V) diagrams for giants and dwarfs at metallicities 0, -0.5, -1.0, -1.5 and -2.0 which are used for thick disc and halo populations

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

$$L = ln \sum dP_i = \sum_i (-q_i + f_i \ln q_i - \ln f_i!) \qquad (2)$$

In search for the models that maximize L it is convenient to use the reduced form:

$$L - L_0 = \sum_i f_i (1 - \frac{q_i}{f_i} + ln \frac{q_i}{f_i}) \qquad (3)$$

4.2. *Confidence interval*

The problem of defining a confidence interval comes from the fact that we do not know how to describe the statistics of errors in the data. The Poisson noise and random errors in the photometry do not explain the differences between independent observations of close fields on the sky (see Fig. 1). A third source of error may come from systematic errors in the photometry. An attempt has been made to compute the statistics of error from the comparison of data sets towards the pole and the anticentre. It appears that neither the number of stars in adjacent bins nor the gradient between star numbers in adjacent bins can be used to make an estimator of error on the data. However we can estimate the likelihood for two data sets to come from the same true star distributions. Using Stobie & Ishida and Soubiran data we obtain a likelihood of -227 for the bins in common, which corresponds to about 15 sigmas difference (Poisson noise). The comparison between SI and GRH gives -103 (about 13 sigmas).

We may estimate the confidence interval of our fit by computing the Poisson noise using several simulations of similar models. The likelihood of two realizations of the same model, differing just by the Poisson statistics, gives the value to add to the maximum likelihood to get the confidence level.

5. Thick disc characteristics

The distributions in the (V, B-V) plane only has been used to determine the structural parameters of the thick disc, because they are more numerous and generally are deeper than U-B data. We compare the number of stars in (V, B-V) bins obtained by model simulations with data. The thick disc is modelled using the density law given in Eq. 4.

$$\rho \propto \begin{cases} \exp(-\frac{R-R_{\odot}}{h_R}) * (1 - \frac{1/h_z}{x_l*(2.+x_l/h_z)} * z^2) & \text{if } z \leq x_l \\ \exp(-\frac{R-R_{\odot}}{h_R}) * \exp(-\frac{z}{h_z}) & \text{if } z > x_l \end{cases} \qquad (4)$$

This density law is radially exponential and vertically exponential for large z. Three parameters define the density along the z axis: h_z, the scale height, ρ_0 the local density and x_l the distance above the plane where the density law becomes exponential. This third parameter is fixed by continuity of $\rho(z)$ and its derivative. It allows the derivability of the density law in the plane and to accurately fit the density law derived from the potential using the Boltzmann equation (see Bienaymé et al. 1987). Hence the parameter x_l varies with the choice of scale height and local density following the potential. Its variation can be approximated by Eq. 5:

$$\begin{aligned} x_l = & \ 1358.6 - 1.35 * nh + 2.335^{-4} * nh^2 \\ & -nr * (8.1775^{-1} + 5.817 * 10^{-3} * nh) \end{aligned} \qquad (5)$$

where

$$nh = \frac{h_z}{1.pc}$$

and

$$nr = \frac{\rho_0}{1.22 * 10^{-3} stars\ pc^{-3}}$$

5.1. *Scale height and local density*

The maximum likelihood method was first applied to the data towards the galactic poles in order to measure the scale height and local normalization independently from the scale length. The data were binned generally by 0.1 magnitude in B-V and 1 magnitude in V, but the data at magnitude fainter than 20 on small fields were binned by 2 magnitudes to get a sufficient number of stars per bin. We restrict our analysis to the domain defined by V>13, 0.4<B-V<(B-V)$_{max}$ where (B-V)$_{max}$ depends on the limiting magnitude of the sample. We use a (B-V)$_{max}$ of 1.0 for Schmidt data, 0.8 for Friel & Cudworth data (limited to

Table 1. Maximum likelihood values for each data set used in the determination of the scale height h_z and normalization ρ_0 of the thick disc towards the galactic pole. L_{Poiss} is the likelihood computed between two realizations from the same model

Data set	h_z (pc)	ρ_0 (% of disc)	L_{max}	L_{Poiss}
Stobie & Ishida	750.	6.1	-113.6	-32.2
Gilmore et. al.	800.	4.9	-107.5	-6.5
Majewski	700.	6.6	-59.0	-2.0
Koo & Kron	840.	6.3	-10.2.	-0.5
All	760.	5.6	-299.	-41.2

magnitude 15), 1.6 for deep counts to magnitude 22. This selection allows to avoid the region of the magnitude-colour diagram where there are few thick disc stars in regards to thin disc stars. It reduces the contamination by disc stars.

A grid of models has been computed with scale heights varying between 480 and 1500 pc and local density between 1% to 15% the one of the disc.

When analyzing likelihood results field by field it appears that small fields cannot constrain the free parameters: On a statistical basis all values of scale height and normalization are compatible with the data. This is true for Fenkart & Esin-Yilmaz and Spaenhauer data and also for Ratnatunga data because no real constraints on the thick disc can be obtained at magnitude brighter than 14. At such magnitudes thick disc stars are mainly subgiants and giants, they are too scarce, even in 20 square degrees. But for fields obtained from deep Schmidt plates the statistics is good and the simulations are sensitive to the thick disc model. Figure 4 shows contours of equal likelihood obtained for different values of scale eight and local density. Only the contours which are at less than 3 sigma are shown. The maximum likelihood obtained for each field and the corresponding Poisson noise is given in Table 1.

Koo & Kron data are of little use because the number of stars is too small to give a significant constraint. There is a very good agreement between data from Stobie & Ishida, Gilmore et al., and Majewski. They all together give a scale height of 760 ± 50 pc with a local density of 5.6 ± 0.8 % of the disc density.

5.2. Scale length

The scale length can be derived from data at intermediate latitudes (GCIL, Aquarius, Serpens, SA54, SA94, SA68, SA51, ACIL). The mean galactocentric distances of thick disc stars in the different fields studied range between 7 kpc (for GCIL and Aquarius) and 9.5 (for SA54 and ACIL) up to 11 kpc for SA51 (but for very few stars), assuming $R_\odot$=8.5 kpc. As in the analysis of the scale height small fields do not give strong constraints on the scale length.

In the case the intermediate latitude fields would give different result for the local density than the pole fields we solve for both parameters, scale length and local normalization (in the range of values allowed by the test towards the pole) for each field and for all fields together. We assume a scale height of 760 pc, as found in the test towards the pole. Figure 5 shows the likelihood obtained for each data set as a function of the scale length and local density of the thick disc. The three curves are at 1,2 and 3 sigmas respectively. The centre field constrains the scale length to be quite small (less than 2.5) if the local density is small (less than 5%) while the anticentre field gives a looser constraint for a larger scale length if the local density is small. The antirotation field only constrains the local density and obviously not the scale length. The resulting local density (5.6% ± 0.6) is in perfect agreement with the value found using the pole fields, and the scale length is 2.8 $\pm^{0.8}_{0.5}$.

We conclude that the thick disc population can be described by a radially exponential density law with a scale length of 2.8 kpc, a modified exponential perpendicular to the plane with a scale height of 760 pc and a local density of 5.6% of the disc.

Compared to the thin disc scale length, our result indicates a value of the same order. Robin et al. (1992) found from star counts towards the anticenter in the plane, that the old disc scale length is 2.5 ±0.3 kpc. Fux & Martinet (1994) found the same value from stellar kinematics in the solar neighbourhood. From COBE data, a 3 kpc projected scale length has been estimated, a result well compatible with these studies. Concerning the thick disc scale length few reliable measurements are available. In Ojha et al. (1995, in preparation) the data used in the present investigation have been pre-analyzed. From a classical estimation of the density ratios between the centre and the anticentre a scale length in the range 2 to 4 kpc has been obtained, the scale height is 760 ± 50 pc and the thick disc over thin disc density ratio 7.4 $^{+2.5}_{-1.5}$ %. Considering the larger uncertainties in the method involving smaller samples their result is well in agreement with ours.

Reid & Majewski claimed from an analysis of Majewski data that the thick disc has a scale height larger than 1400 pc. Our study favours, from the same data, a scale height of 760 pc. The reason is found in the different models of disc used in both analysis. In RM models the discs make the major part of stars at B-V>1.4 at V~21, while in the Besançon model one get a mixture of disc and thick disc. The disc has been carefully adjusted to data from magnitude 5 (Hipparcos Input Catalogue) up to 22 (Prime focus plates and CCDs), and Schmidt data at intermediates magnitude (Haywood 1994; Haywood et al. 1995 in preparation), while this is not the case for RM model. Finally, our result is reinforced by the consistency between results at high and intermediate latitudes in numerous fields.

In order to estimate the influence of the thin disc model on the adjusted thick disc, we attempted to use a self consistent thin disc model computed with a maximum velocity dispersion of 18 km/s in place of 21 used in simulations presented above. The adjusted thick disc characteristics are very closed to previous ones, giving a slightly higher local density (to compensate the smaller thin disc) but the difference is at less than 1 sigma. Moreover the likelihood obtained with this thinner disc is slightly smaller than with a thin disc of $\sigma_{W max}$ = 21 km/s.

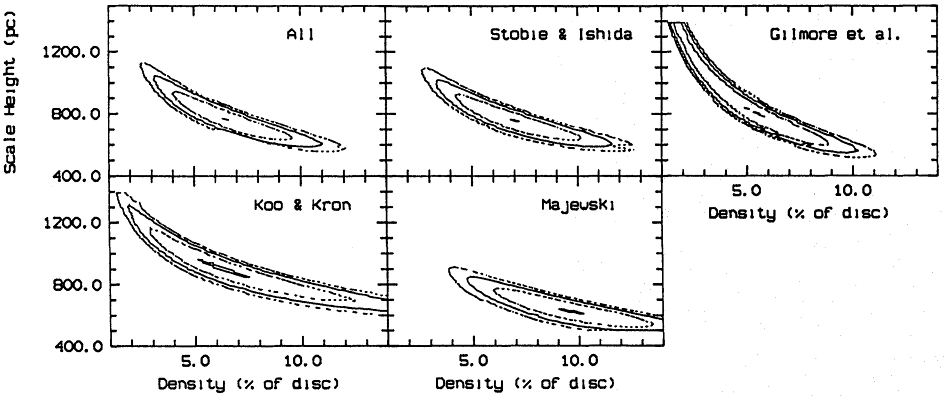

Fig. 4a–e. Contours of equal likelihood as a function of local density and scale height of the thick disc population towards the galactic poles. **a** All fields; **b** Stobie & Ishida; **c** Gilmore et al.; **d** Koo & Kron; **e** Majewski. The contours are at 1, 2 and 3 sigmas

5.3. Luminosity function

In this study we assume that the luminosity function of the thick disc is similar to the one of 47 Tuc. Can we constrain this function using these data and would the choice of the LF influence the result on the density ?

The shape of the luminosity function depends mainly on three parameters: the age, the slope of the Initial Mass Function and the metallicity, assuming that the thick disc formed on a small time scale relative to the age of the Galaxy. The metallicity is derived from colour informations (sect. 5). The age parameter fixes the absolute magnitude of the turnoff, where the LF is the steepest. A difference of 4 Gyr gives a shift of 0.4 magnitude only. Turnoff stars of the thick disc appear in star counts at high latitude at about 14-15 V magnitude. Available counts are still not sufficient to constrain such a small absolute magnitude shift.

Luminosity functions computed by Bergbush & Vandenberg (1992) vary most significantly at the level of faint stars for different IMF ($M_V > 9$). We used their models to test two hypothesis for the IMF slope (x=0.5 and x=1.0). The maximum likelihood was computed for two apparent magnitude ranges: 15-17 and 17-22. The ratio of the number of stars in both ranges gives a constrain independent from the scale height. The best agreement between model and data is obtained with a slope of x=1 but a slope of 0.5 cannot be rules out at a 1 sigma level.

5.4. Abundances

Colour distributions are also sensitive to the metal abundances of the populations. While U-B is more sensitive to the metallicity, B-V data tend to be more accurate. This is the reason why we attempt to estimate the mean metallicities and gradients of the various populations using separately the (V,B-V) plane and the (V,U-B) plane. In the case of U-B we restrict our analysis to 7 fields (North Galactic Pole, from Spaenhauer 1989, from Fenkart & Esin-Yilmaz 1985, between 10 and 18, from Koo & Kron 1982 between 20 and 22, (l=4, b=47) from Ojha et al. 1994a, (l=169, b=47) from Ojha et al. 1994b, SA54 from Fenkart & Esin-Yilmaz 1983).

Starting with a simulated catalogue for each data set, we compute for each star its colours assuming different metallicities. Then we compute the resulting (V, U-B) and (V, B-V) distributions and compare them with real data. We apply the same maximum likelihood test as in the previous section. Colour data are binned in steps of 0.1 magnitude and V in steps of 1 magnitude, restricted to V>14 and U-B<1.2.

Table 2. Range of acceptable values for the mean metallicity of the thick disc obtained by maximum likelihood test, at 1 sigma level, as described in the text

Data set	L_{max}	[Fe/H]	$L_{Poisson}$	Range
Pole SI	-290.	-0.5	-90.	[-0.4, -0.7]
Pole Spaenhauer	-28	-1.0	-5.4	[-0.6, -1.3]
Pole FEY	-26	-1.0	-4.2	[-0.7, -1.3]
Centre GCIL	-426	-0.8	-98	[-0.6, -1.0]
Centre Aquarius	-1229	-0.8	-64	[-0.6, -1.0]
Anticentre YY	-127	-0.7	-75	[-0.5, -1.0]
Anticentre ACIL	-50	-0.9	-52	[-0.5, -1.3]
Anticentre FEY	-34	-1.1	-4.3	[-0.9, -1.2]
All	-2383	-0.7	-342	[-0.6, -0.9]

Using this method we solve for several parameters simultaneously: the mean metallicity of the thick disc and the radial and vertical gradients of the thin disc.

Figure 6 shows the resulting likelihoods obtained for the thick disc mean metallicity. Table 3 gives the values of maximum likelihood and acceptable 1 sigma range field by field. The confidence interval is computed following the method described in Sect. 4. All fields together give a mean metallicity of -0.7 ± 0.2. We find no noticeable gradient of abundances between centre and anticentre fields.

Exploring the possibility that the halo metallicity influences the result, we found that the available data do not go deep enough in V to get sufficient information on the metallicity of the halo and, conversely, that its adopted value does not influence the result about the thick disc metallicity.

An attempt has been made to measure the metallicity gradients in the thin disc population. The radial gradient was found in the range 0 to -0.2 dex kpc^{-1}, values less compelling than what can be obtained by direct measurements of metallicities in stellar samples. Concerning the vertical gradient, values obtained using different samples are contradictory. SI data towards the pole are in favour of a small gradient of -0.25 dex kpc^{-1},

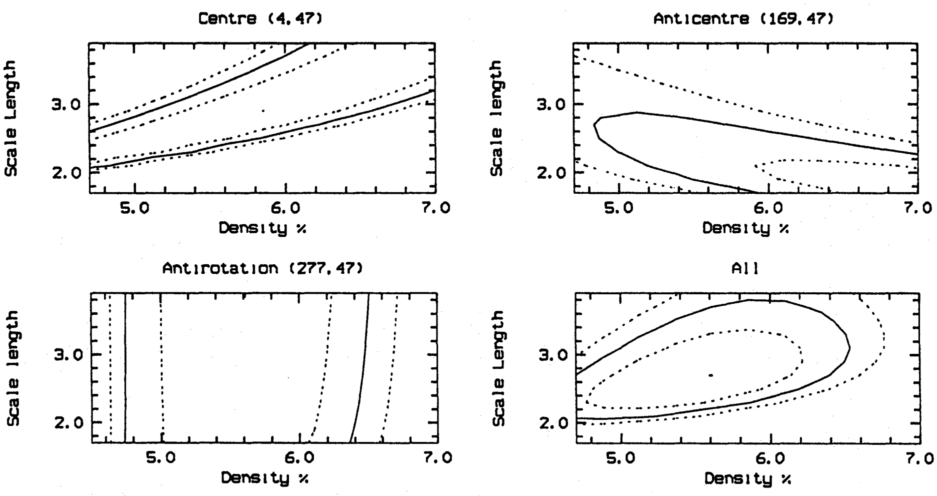

Fig. 5a–d. Likelihood as a function of the scale length and local density computed from fields: **a** GCIL (4,47); **b** ACIL (169,47); **c** ARIL (278,47); **d** All fields together

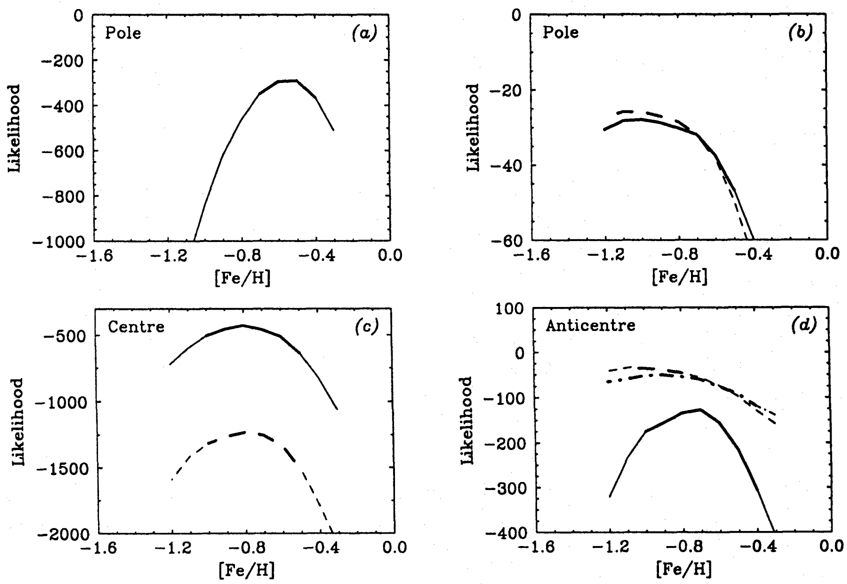

Fig. 6a–d. Likelihood obtained for different samples as a function of the mean metallicity of the thick disc. **a** Pole Schmidt data (Stobie & Ishida); **b** Pole, other data (solid line: Spaenhauer, dashed line: Fenkart & Esin-Yilmaz, dotted-dashed: Koo & Kron); **c** GCIL field (l=4, b=47, solid line) and Aquarius (37, -51, dashed line); **d** Anticentre fields (Solid line: Yamagata & Yoshii (SA54), dashed line: Ojha et al. (l=169, b=47), dotted-dashed: Fenkart & Esin-Yilmaz (SA54). In bold the range of acceptable values

YY data in SA54 give a high value of -0.65, while FEY favour -0.15 dex kpc^{-1}. Ojha (1994a) data in ACIL field are nearly insensitive to this parameter. We conclude that this effect is at the limit of the accuracy of the present data.

6. Thick disc formation

Two families of scenarii are advocated to explain the formation of the thick disc. The first family features 'pre-thin disc' or 'top-down' models where the thick disc forms through a dissipational collapse, after the halo formation and before the thin disc has completely collapsed. In top down scenarii thick disc stars form during late phases of the collapse, which means either a slow collapse or a high star formation rate during these phases. Slow down collapse regimes generate chemical and kinematical gradients which would be clear signatures of such a process. In contrast, top-down models with enhanced star formation offer a possible gradient-free mechanism. However, playing freely with ad-hoc star formation rate, in the absence of an identified enhancement mechanism looks quite arbitrary. We show elsewhere (Haywood et al. 1995) that along the whole thin disc lifetime the star formation rate has been stable or slightly increasing. Along the same lines, top-down scenarii hardly generate a discontinuity between thick disc and thin disc, unless some ad-hoc mechanism switches off star formation during a transition phase.

The second type of models are called 'post-thin disc'. They resort to formation of the thick disc after the gas has completely collapsed into a thin disc. Possible physical processes are: 1) Secular kinematic diffusion of thin disc stars. In this case the thick disc is a prolongation of the thin disc, the gradients visible in the thin disc should appear in the thick disc. 2) Violent thin disc heating by the accretion of a satellite galaxy (The required event(s) must not occur too late in the disc life time so that the gas can cool again and form stars in the long-lasting thin galactic disc. 3) Accretion of a satellite galaxy without heating of the thin disc (thick disc is formed of the debris of the satellite(s)). These last two scenarii can be combined.

The violent bottom up scenario leaves two important observational signatures. First the thick disc is a separate population distinct from the thin disc and the halo. Second no gradient can be generated in the thick disc by the event, although a pre-existing gradient may survive the merger. One can compare the thick disc observed characteristics with these different signatures.

1. *There is a change of slope in the density law between thin and thick disc.* The scale heights obtained for the thin and thick disc are strongly different. Haywood (1994) shows, from an analysis of numerous star counts towards the pole using his self-consistent evolutionary model, that the thin disc scale height does not exceed 250 pc (K dwarfs). This result is confirmed by Ojha (1994) from a standard analysis of stellar densities towards the pole. A similar result has also been obtained by Kroupa (1992): A scale height of 270 pc for stars of $M_V > 6$. In the present paper the thick disc is shown to have a scale height of 760 ± 50 pc using a synthesis approach free of bias. Same value is also obtained from a classical analysis of star counts by Ojha et al. (1994ab) and Soubiran (1993).
   The three basic quantities characterizing the thick disc density distribution (local density, scale height, scale length) are tightly and consistently constrained by the global analysis over different fields at various latitudes and longitudes, a consistency which had never been obtained by previous studies.
   Hence density laws show a true discontinuity between thin disc and thick disc populations.
2. *The thick disc is kinematically distinct from the thin disc and from the halo; it shows no kinematic gradients.* Kinematic data from Ojha et al. (1994ab) use a SEM algorithm to estimate the number of Gaussian components present in proper motion data towards 3 directions at intermediate latitude. In the SEM analysis, discrete Gaussian kinematic components are considered. The data do support this hypothesis, although more complex distribution functions might be valid. In all cases they obtain a clear separation between a thin and a thick population. For example, towards the anticentre (Ojha et al. 1994):

   $$\sigma_{\frac{U+W}{\sqrt{2}}})_{thick} - \sigma_{\frac{U+W}{\sqrt{2}}})_{thin} = 30 \pm 3kms^{-1}$$

   $$\sigma_V)_{thick} - \sigma_V)_{thin} = 30 \pm 3kms^{-1}$$

   Asymmetric drift :

   $$< V >_{thick} - < V >_{thin} = 45 \pm 4kms^{-1}$$

   All recent studies of the asymmetric drift of the thick disc converge to small values (about 40 km s^{-1}, Ojha 1994). Most authors do not find any vertical gradient in any of the three fields. However Majewski (1992) invokes such gradient and, on this basis, advocates a dissipational collapse for the thick disc. His Fig. 6 shows a number of results from different samples of supposed thick disc stars. However most data are selected sample based on the metallicity and proper motions. These samples are generally contaminated by disc stars at low z and by halo stars at high z. It has been shown by Ojha et al. (1994ab) and by Soubiran (1993) that, when one separates the populations on a statistical basis by multi-Gaussian fitting without a priori informations on them, one can separate a thin disc from a thick disc and the asymmetric drift shows no gradient with z inside the thick disc population itself. Moreover no velocity dispersion gradient is observed inside the thick disc (Ojha et al. 1994ab).
   On the other hand there is a large gap of circular velocity between the thick disc (180 km s^{-1}) and the halo (0 ± 40 km s^{-1}), proving the disentangling of these two populations.
   Hence the kinematics of the thick disc shows that it is a population distinct from the thin disc and from the halo and that no vertical gradient is present. Both arguments are incompatible with a 'top-down' scenario of formation for the thick disc.
3. *Thick disc stars show no vertical abundance gradient* However the U-B star counts may be suspected of systematic errors we find that the thick disc has a mean metallicity [Fe/H] of -0.7 dex and find no evidence for a vertical gradient of this quantity. This result is confirmed by observations of Gilmore & Wyse (1995) of F/G thick disc stars. They also obtain a mean [Fe/H] of -0.7 dex and no metallicity gradient in the distance range 500 to 3000 pc. This result argues against a 'top-down' model of thick disc with a slow dissipational collapse, although this argument cannot throw away a top-down model with fast collapse and a very high star formation rate. On the other hand, QHF simulations of the merging scenario show that the event does not alter substantially the pre-existing gradient, if any. Observations of no abundance gradient in the thick disc imply no previous gradient in the thin disc. This is consistent with our observations that the thin disc actually has no metallicity gradient, apart from the one produced by orbit diffusions.

All observed characteristics favour a post-thin disc formation for the thick disc. If this is caused by a secular heating of the thin disc one should see a continuity with the thin disc. The large σ_W of the thick disc implies a heating process particularly efficient and on a short period (the σ_W of the thick disc is about 42 km s^{-1} while the disc does not exceed 21 km s^{-1}) (Haywood 1994). Hence this scenario is rejected by the observations. We stay with two scenarii related to the merging of a satellite galaxy with the Milky Way. Statler (1988) studied the possibilities that a merging satellite leaves a part of its material in the Galaxy. He showed that the residuals should form a peanut shaped bulge but also form a kind of thick layer. However he did not study the impact on the thin disc of this accretion. This scenario is only valid if the accretion is made of small satellites in order to conserve a thin disc. Quinn et al. (1993, hereafter QHF) analyze a scenario of satellite accretion by a spiral galaxy. A thick disc may be produced by the dynamical heating of the thin disc. The resulting thick disc has typical characteristics that may be compared with our new measurements of the thick disc of the Galaxy. No vertical kinematic gradients should be present, an abundance gradient may be present only if it was present before the event. In the example given by QHF the resulting thick disc has a scale height of 750 pc in the solar neighbourhood with projected values ranging from 850 to 1200 pc in the galactocentric distance range $7 < R < 10.5$. Although we do not see any rise of it with radius, this is not excluded because few stars are reached at large enough distances. For the same reason the rise of velocity dispersion in the external part of the Galaxy, implied by the QHF model, is significant at too large distances to be seen in the Ojha et al. data.

We conclude that the characteristics of the thick disc as measured by photometric and proper motion star counts show a population quite distinct from the thin disc and well in agreement with a disruptive accretion scenario. These characteristics do exclude thick disc formation via slow dissipative collapse prior to the formation of the (thin) disc. Other interpretations can be built, based on abrupt *ad hoc* variations of the star formation rate, although tuning such interpretations to combined kinematic and photometric constraints looks rather arbitrary.

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