Galactic structure studies from the Beijing–Arizona–Taiwan–Connecticut survey

Cuihua Du,1,2* Jun Ma,2 Zhenyu Wu2 and Xu Zhou2

1College of Physical Sciences, Graduate University of the Chinese Academy of Sciences, Beijing 100049, China
2National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

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ABSTRACT

We present an analysis of the photometric parallaxes of stars in 21 of the Beijing–Arizona–Taiwan–Connecticut Survey fields carried out with the National Astronomical Observatories (NAOC) 60/90 cm Schmidt Telescope in 15 intermediate-band filters from 3000 to 10 000 Å. In this study, we have adopted a three-component (thin disc, thick disc and halo) model to analyse star count information. By calculating the stellar space density as a function of distance from the Galactic plane, we determine that the range of scaleheight for the thin disc varies from 220 to 320 pc. Although 220 pc seems an extreme value, it is close to the lower limit in the literature. The range of scaleheight for the thick disc is from 600 to 1100 pc, and the corresponding space number density normalization is 7.0–1.0 per cent of the thin disc. We find that the scaleheight of the disc may be variable with the observed direction, which cannot simply be attributed to statistical errors. Possibly the main reasons can be attributed to the disc (mainly the thick disc) being flared, with a scaleheight increasing with radius. The structure is consistent with the merger origin for the thick disc formation. Adopting a de Vaucouleurs $r^{1/4}$ law halo, we also find that the axis ratio towards the Galactic Centre is somewhat flatter ($\sim 0.4$), while the shape of the halo in the anticentre and antirotation direction is rounder with $c/a > 0.4$. Our results show that star counts in different lines of sight can be used directly to obtain a rough estimate of the shape of the stellar halo. Our solutions support the Galactic models with a flattened inner halo, possibly formed by an early merger in the Galaxy’s history.

Key words: Galaxy: fundamental parameters – Galaxy: halo – Galaxy: stellar content – Galaxy: structure.

1 INTRODUCTION

Detailed study of the Galactic structure enables us to address many important questions in astrophysics, because it is only in the Milky Way that we can make detailed studies. However, since we observe our Galaxy from within, we must use indirect tools such as star counts to probe its structure (Peiris 2000). The star count method, which is predominantly used to study the general properties of the Galaxy, is a very effective way of constraining the structural parameters for the components of the Galaxy, while the density distribution of the Galaxy components is assumed similar to those of galaxies of the same Hubble type. In the standard model (Bahcall & Soneira 1980), the Galaxy is of Hubble type Sbc, consisting of an exponential disc and a spherical halo.

Over the past decades, considerable efforts have been undertaken to gain information about the structure and history of the formation and evolution of our Galaxy. Galactic structure models of varying degrees of complexity have been developed (Bahcall & Soneira 1980, 1984; Gilmore 1984; Robin & Crézé 1986; Reid & Majewski 1993; Méndez et al. 1996; Siegel, Majewski & Reid 2002). It is now apparent from several independent avenues of research that our Milky Way is a much more complex system than we thought before.

Bahcall & Soneira (1980) established the first standard model, in which the Galaxy was simplified and parametrized by an exponential disc and a spheroid, the latter is characterized by a de Vaucouleurs profile. Later, further studies on this subject showed that the number of population components of the Galaxy increased from two to three. This new component (the thick disc) was introduced by Gilmore & Reid (1983), based on star counts towards the South Galactic Pole. The new component is discussed by Gilmore & Wyse (1985) and Wyse & Gilmore (1986). The stellar population of the thick disc is distinct from that of the halo, and its existence is seen clearly in colour–magnitude diagrams derived from the star count survey (Gilmore, Wyse & Kuijken 1989; Chen, Stoughton & Smith 2001).

Following the work of Gilmore & Reid (1983), the three-component model including the thin disc, thick disc and spheroid (halo) has

*E-mail: ducuihua@gucas.ac.cn
become a common model for our Galaxy and has been used widely.

Up to now, the basic stellar components of the Milky Way have been taken to be the thin disc, the thick disc, the stellar halo and the central bulge, albeit that the inter-relationships and the distinction amongst different components remain subject to some debate (Lemon et al. 2004). In previous works, various models have been developed to describe the stellar populations of the Galaxy. In general, these models were based on the assumption of a suitable spatial density distribution, and on the observational luminosity function and colour–magnitude diagram for each stellar population (Bahcall & Soneira 1984; Reid & Majewski 1993) to fit the structural parameters by exploiting the measurements of colour and magnitudes. The canonical spatial density distribution is as follows: stellar distribution for the thin and thick discs in cylindrical coordinates by radial and vertical exponentials law and for the halo by the de Vaucouleurs spheroid (Du et al. 2003; Karaali, Bilir & Hamzaoglu 2004). Thus, the structure parameters can be deduced by comparing the model and the star count data. Different parametrizations of the Galactic components were tried by many authors (Bahcall & Soneira 1980; Gilmore 1984; Ojha et al. 1996; Chen et al. 2001; Karaali et al. 2003, 2004; Du et al. 2003; Du, Zhou & Ma 2004a; Kaempf, de Boer & Altmann 2005). However, due to different and conflicting results from the modelling of star counts, the spatial distribution of the Galactic components remains controversial. There is still some uncertainty about the exact characteristics of each Galactic component. However, quantifying the properties of the stellar components of the Galaxy is of wide importance; they are closely related to stellar quantities such as distance, age, metallicity and kinematics characteristics, which are necessary for understanding the formation and evolution of the Galaxy (Du et al. 2004b; Pohlen et al. 2004; Brook et al. 2005). These properties can be obtained by straightforward photometric and spectroscopic observation. At present, before full exploitation of the huge spectral surveys (e.g. GAIA, SEGUE, LAMOST, etc.) is possible, star counts based on all-sky photometric surveys is one of the few accessible methods for the study of the Galactic structure.

In this study, to better understand and study the Galactic structure, the Beijing–Arizona–Taiwan–Connecticut (BATC) multicolour photometric survey further provides more new catalogues with the achievement of data observation and reduction. These catalogues are very useful in constraining the structure of the main components of the Galaxy. We will report our investigation of star count extending our research to include different direction data. The present discussion is a more complete and sophisticated investigation of a number of BATC-selected fields. Section 2 describes the details of observations and data reduction. The object classification and the photometric parallaxes are found in Section 3. Section 4 deals with the space density distribution of stars in the direction used in this study. Finally, we summarize and discuss our main conclusions.

## 2 BATC OBSERVATIONS

### 2.1 BATC photometric system and data reduction

The BATC survey performs photometric observations with a large field multicolour system. There are 15 intermediate-band filters in the BATC filter system, which covers an optical wavelength range from 3000 to 10 000 Å (Fan et al. 1996; Zhou et al. 2001). The 60/90 cm f/3 Schmidt Telescope of National Astronomical Observatories (NAOC) was used, with a Ford Aerospace 2048 × 2048 CCD camera at its main focus. The field of view of the CCD is 58 × 58 arcmin² with a pixel scale of 1.7 arcsec.

The definition of the magnitude for the BATC survey is in the AB system, which is a monochromatic flux system first introduced by Oke & Gunn (1983). The four Oke & Gunn (1983) standards which are used for flux calibration in the BATC survey are HD19445, HD84937, BD+262606 and BD+174708. The fluxes of the four stars have been recalibrated by Fukugita et al. (1996). Their magnitudes in the BATC system have slightly been corrected by cross-checking with the data obtained on a number of photometric nights (Zhou et al. 2001).

Preliminary reductions of CCD frames, including bias subtraction and flat-fielding correction, were carried out with an automatic data reduction procedure called PIPELINE I, which has been developed for the BATC survey (Fan et al. 1996). The Hubble Space Telescope Guide star catalogue (GSC) (Jenkner et al. 1990) was then used for coordinate determination.

A PIPELINE II program based on the DAOPHOT II stellar photometric reduction package of Stetson (1987) was used to measure the magnitudes of point sources in the BATC CCD frames. The PIPELINE II reduction procedure was performed on each single CCD frame to get the point spread function (PSF) magnitude of each point source. The magnitudes were then calibrated to the BATC standard system (Zhou et al. 2003). The other sources of photometric error, including photo star and sky statistics, readout noise, random and systematic error from bias subtraction and flat-fielding, and the PSF fitting, are all considered in PIPELINE II. The total estimated errors of each star are given in the final catalogue (Zhou et al. 2003). Stars that are detected in at least three filters are included in the final catalogue.

In Table 1, we list the parameters of the BATC filters. Columns 1 and 2 represent the ID of the BATC filters, whereas columns 3 and 4 represent the central wavelengths and FWHM of the 15 BATC filters, respectively.

### 2.2 The directions

Most previous investigations have focused upon one or a few selected line-of-sight directions generally either in small areas to great depth or over a large area to shallower depth (e.g. Gilmore & Reid 1983; Bahcall & Soneira 1984; Reid & Majewski 1993; Reid et al. 1996). The deep fields are small with corresponding poor

<table>
<thead>
<tr>
<th>No.</th>
<th>Filter</th>
<th>Wavelength (Å)</th>
<th>FWHM (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>3371.5</td>
<td>359</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>3906.9</td>
<td>291</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
<td>4193.5</td>
<td>309</td>
</tr>
<tr>
<td>4</td>
<td>d</td>
<td>4540.0</td>
<td>332</td>
</tr>
<tr>
<td>5</td>
<td>e</td>
<td>4925.0</td>
<td>374</td>
</tr>
<tr>
<td>6</td>
<td>f</td>
<td>5266.8</td>
<td>344</td>
</tr>
<tr>
<td>7</td>
<td>g</td>
<td>5789.9</td>
<td>289</td>
</tr>
<tr>
<td>8</td>
<td>h</td>
<td>6073.9</td>
<td>308</td>
</tr>
<tr>
<td>9</td>
<td>i</td>
<td>6655.9</td>
<td>491</td>
</tr>
<tr>
<td>10</td>
<td>j</td>
<td>7057.4</td>
<td>238</td>
</tr>
<tr>
<td>11</td>
<td>k</td>
<td>7546.3</td>
<td>192</td>
</tr>
<tr>
<td>12</td>
<td>m</td>
<td>8023.2</td>
<td>255</td>
</tr>
<tr>
<td>13</td>
<td>n</td>
<td>8484.3</td>
<td>167</td>
</tr>
<tr>
<td>14</td>
<td>o</td>
<td>9182.2</td>
<td>247</td>
</tr>
<tr>
<td>15</td>
<td>p</td>
<td>9738.5</td>
<td>275</td>
</tr>
</tbody>
</table>
statistical weight, and the large fields are limited with shallower depth which may not be able to probe the Galaxy at large distance (Karaali et al. 2004). However, the investigation into Galactic structure, such as quantifying the properties of the stellar components and substructure of the Galaxy, obviously benefits from large-scale surveys. In addition, the evaluation of star counts in a single direction can lead to degenerate density-law solution. For instance, increasing the normalization of the Galactic spheroid and decreasing its axis ratio represent a degeneracy. This means that in most directions, one cannot distinguish between models with a flattened spheroid plus a low normalization ratio of spheroid stars to disc stars, and those with a high axis ratio plus a high normalization (Peiris 2000). Up to now, only a few programmes survey the Galaxy in multiple directions such as the Basle Halo Program (Buser, Rong & Karaali 1999), the Besançon programme (Robin, Haywood & Crézé 1996; Robin et al. 2003), the APS-POSS programme (Larsen & Humphrey 1996) and the SDSS (Chen et al. 2001).

In this paper, the BATC photometry survey presented 21 selected fields in the multiple directions. Each field of view is \(\sim 1\) deg\(^2\). Table 2 lists the locations of the observed fields towards the Galactic Centre and their general characteristics. In Table 2, column 1 represents the BATC field name; columns 2 and 3 represent the right ascension (RA) and declination (Dec.), respectively; column 4 represents the epoch; columns 5 and 6 represent the Galactic longitude and latitude, and the last two columns represent the mean reddening and limit magnitude, respectively. The mean reddening \([E(B - V)]\) was determined using the maps of Burstein & Heiles (1982).

There are 15 intermediate-band filters with an optical wavelength range from 3000 to 10 000 Å in the BATC multicolour system. Every object observed in all BATC fields could be classified according to their spectral energy distribution (SED) information constructed from the 15-colour photometric catalogue. Here, because our fields in this work have also been observed by the Sloan Digital Space Survey (SDSS-DR4) and each object type (stars–galaxies–QSO) has been given, we can obtain a relative reliable star catalogue.

The observed colour of each star is compared with a colour library of known stars with the same photometric system. The input library for stellar spectra is the Pickles (1998) catalogue. This library consists of 131 flux-calibrated spectra, including all normal spectral types and luminosity classes at solar abundance, and metal-poor and metal-rich F–G dwarfs and G–K giant components. Our sample may contain stars spread over a range of different metallicities. In Fig. 1, the two-colour diagram \((d–i) \text{ versus } (i–m)\) is shown for our sample. The panel (a) represents the northern sample (north of the Galactic plane), and the panel (b) represents the southern sample (south of the Galactic plane). Although the 15 filters are used in the object classification, the two-colour diagram based only on the \(d, I\) and \(m\) filters and used as an example shows that the scatter still exists in our sample. Most of the stars lie in the mean main-sequence track, and for those objects beyond the track the scatter can be mainly due to the metallicity effect and contamination from a few non-main-sequence stars.

For those stars, the probability of belonging to a certain star class is computed by the SED fitting method. The standard \(\chi^2\) minimization, i.e. computing and minimizing the deviations between the photometric SED of a star and the template SEDs obtained with

<table>
<thead>
<tr>
<th>Observed field</th>
<th>RA</th>
<th>Dec.</th>
<th>epoch</th>
<th>(l) (°)</th>
<th>(b) (°)</th>
<th>([E(B - V)])</th>
<th>(i) (comp)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8:38:02</td>
<td>44:58:38</td>
<td>1950</td>
<td>175.7</td>
<td>37.8</td>
<td>0.03</td>
<td>21.0</td>
</tr>
<tr>
<td>T518</td>
<td>9:54:05</td>
<td>−0:13:24</td>
<td>1950</td>
<td>238.9</td>
<td>39.8</td>
<td>0.03</td>
<td>19.5</td>
</tr>
<tr>
<td>T288</td>
<td>8:42:30</td>
<td>34:31:54</td>
<td>1950</td>
<td>189.0</td>
<td>37.5</td>
<td>0.02</td>
<td>20.0</td>
</tr>
<tr>
<td>T477</td>
<td>8:45:48</td>
<td>45:01:17</td>
<td>1950</td>
<td>175.7</td>
<td>39.2</td>
<td>0.03</td>
<td>20.0</td>
</tr>
<tr>
<td>T328</td>
<td>9:10:57</td>
<td>56:25:49</td>
<td>1950</td>
<td>160.3</td>
<td>41.9</td>
<td>0.03</td>
<td>19.5</td>
</tr>
<tr>
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<td>9:13:34</td>
<td>7:15:00</td>
<td>1950</td>
<td>224.1</td>
<td>35.3</td>
<td>0.03</td>
<td>20.5</td>
</tr>
<tr>
<td>TA26</td>
<td>9:19:57</td>
<td>33:44:31</td>
<td>2000</td>
<td>191.1</td>
<td>44.4</td>
<td>0.01</td>
<td>20.0</td>
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<tr>
<td>T291</td>
<td>9:32:00</td>
<td>50:06:42</td>
<td>1950</td>
<td>167.8</td>
<td>46.4</td>
<td>0.01</td>
<td>20.0</td>
</tr>
<tr>
<td>T362</td>
<td>10:47:55</td>
<td>4:46:49</td>
<td>1950</td>
<td>245.7</td>
<td>53.4</td>
<td>0.03</td>
<td>20.0</td>
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<tr>
<td>T330</td>
<td>11:58:02</td>
<td>46:35:29</td>
<td>1950</td>
<td>147.2</td>
<td>68.3</td>
<td>0.00</td>
<td>20.5</td>
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<tr>
<td>U085</td>
<td>12:56:04</td>
<td>56:53:36</td>
<td>1996</td>
<td>121.6</td>
<td>60.2</td>
<td>0.01</td>
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</tr>
<tr>
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<td>0:11:54</td>
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<td>56.1</td>
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<td>20.5</td>
</tr>
<tr>
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<td>−0:02:07</td>
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<td>62.9</td>
<td>−44.0</td>
<td>0.03</td>
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<td>T359</td>
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<td>13:10:46</td>
<td>1950</td>
<td>79.7</td>
<td>−37.8</td>
<td>0.06</td>
<td>20.5</td>
</tr>
<tr>
<td>T350</td>
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<td>12:14:45</td>
<td>1950</td>
<td>251.3</td>
<td>67.3</td>
<td>0.00</td>
<td>19.5</td>
</tr>
<tr>
<td>T354</td>
<td>15:14:34</td>
<td>56:30:33</td>
<td>1950</td>
<td>91.6</td>
<td>51.1</td>
<td>0.01</td>
<td>21.0</td>
</tr>
<tr>
<td>T193</td>
<td>21:55:34</td>
<td>0:46:13</td>
<td>1950</td>
<td>59.8</td>
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<td>0.05</td>
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<td>T516</td>
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<td>125.0</td>
<td>−62.0</td>
<td>0.00</td>
<td>20.0</td>
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<tr>
<td>T329</td>
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<td>47:49:00</td>
<td>1950</td>
<td>169.9</td>
<td>50.4</td>
<td>0.01</td>
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</tr>
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<td>20:29:23</td>
<td>2000</td>
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<td>−62.1</td>
<td>0.00</td>
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</tr>
<tr>
<td>T517</td>
<td>3:51:43</td>
<td>0:10:01</td>
<td>1950</td>
<td>188.6</td>
<td>−38.2</td>
<td>0.12</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Notes: Units of RA are hours, minutes and seconds, and those of Dec. are degrees, arcminutes and arcseconds.

### 3 Object Classification and Photometric Parallaxes

There are 15 intermediate-band filters with an optical wavelength range from 3000 to 10 000 Å in the BATC multicolour system. Every object observed in all BATC fields could be classified according to their spectral energy distribution (SED) information constructed from the 15-colour photometric catalogue. Here, because our fields in this work have also been observed by the Sloan Digital Space Survey (SDSS-DR4) and each object type (stars–galaxies–QSO) has been given, we can obtain a relative reliable star catalogue.

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For those stars, the probability of belonging to a certain star class is computed by the SED fitting method. The standard \(\chi^2\) minimization, i.e. computing and minimizing the deviations between the photometric SED of a star and the template SEDs obtained with
Figure 1. The distribution of \((i-m)\) versus \((d-i)\) for (a) the northern sample (north of the Galactic plane), (b) the southern sample (south of the Galactic plane) down to the limiting magnitude.

...the same photometric system, is used in the fitting process. The minimum \(\chi^2_{\text{min}}\) indicates the best fit to the observed SED by the set of template spectra:

\[
\chi^2 = \sum_{l=1}^{N_{\text{filt}}} \left( \frac{F_{\text{obs},l} - F_{\text{temp},l} - b}{\sigma_l} \right)^2,
\]

where \(F_{\text{obs},l}\), \(F_{\text{temp},l}\) and \(\sigma_l\) are the observed fluxes, template fluxes and their observed uncertainty in filter \(l\), respectively, and \(N_{\text{filt}}\) is the total number of filters in the photometry, while \(b\) is the mean magnitude difference between the observed and template fluxes. Details about the classification of stars could be found in our previous papers about star counts (Du et al. 2003, 2004a).

Thus, we can obtain the spectral types and luminosity classes for stars in the BATC survey. After knowing the stellar type, the photometric parallaxes can be derived by estimating absolute stellar magnitudes. We adopted the absolute magnitude versus stellar type relation for main-sequence stars from Lang (1992). A variety of errors affect the determination of stellar distances. The first source of errors could be from photometric uncertainty, the second from the misclassification and metallicity that affects the derivation of absolute magnitude. In the library adopted in this paper, the term ‘metal-poor’ corresponds to abundance indicator strengths in the range 0.1–0.5 of solar metallicity and ‘metal-rich’ corresponds to abundance indicator strengths in the range 2–6 of solar metallicity. The classification system may only give general metallicity. It is insufficient to distinguish disc from halo stars. This may affect the stellar distances somewhat. In addition, there may be an error by the contamination of binary stars in our sample. We neglect the effect of contamination on distance derivation. For binaries with equal mass components, the distance will be assumed closer by a factor of \(\sqrt{2}\) (Ojha et al. 1996). Due to the unknown but probable mass distribution in binary components, the effect is certainly less severe.

Figure 2. The \((d-i)\) colour distribution of the sample stars in the northern and southern fields.

(Majewski 1992; Kroupa, Tout & Gilmore 1993). Since most fields are at intermediate and high latitude \((b > 35^\circ)\), the error from the interstellar extinction in the distance calculation can be neglected.

4 STELLAR DENSITY DISTRIBUTION

It is well known that the population types are a complex function of both colour and apparent magnitude. Standard star count models indicate that the colour–magnitude range could be used to separate roughly different populations of the Galaxy. In Fig. 2, the \((d-i)\) colour distribution of the sample stars shows a bimodal distribution. The left-hand peak is dominated by halo stars, while the one on the right is dominated by thin disc stars, and the overlap between the halo stars and the thin disc stars is dominated by thick disc stars. Because the halo stars are far more distant than the bulk of...
the disc stars, only the luminous stars in the halo (predominantly main-sequence stars) can be detected. For the main-sequence stars, the intrinsically bright ones have bluer colour. Besides, the halo stars are generally more metal-poor, and hence tend to dominate the blue peak. Similarly, the thin disc stars would form the red peak and the thick disc stars would lie between them. From this figure, we can see that the thick disc and halo populations overlap in the range $(d-i) < 1.4$.

The colour distribution of the sample stars in the T288 field is given as a function of apparent magnitude in Fig. 3. According to Chen et al. (2001), the thick disc has a turn-off of $(g'-r')_0 = 0.33$ and it is dominant at bright apparent magnitudes, $15 < g'_0 < 18$ mag, whereas the halo has a turn-off colour at $(g'-r')_0 = 0.20$ for the apparent magnitude fainter than $g'_0 \sim 18$ mag. Karaali et al. (2003) also consider that the corresponding turn-off colour in the UBVRI system are $(B-V)_0 = 0.41$ and 0.53 for halo and thick disc, respectively. In Fig. 4, we show the observed colour–magnitude diagram $(i, d-i)$ from the northern and southern samples. It seems to show a dominant blue population (including of halo and thick disc) and a second redder population (thick and thin disc). Regarding the population isolation (disc and halo), we mainly use Fig. 3 to give a rough colour limit for a single field. So the disc and halo stars can be generally distinguished from the selected field. The turn-offs for the disc and halo in our sample are also fixed (see Table 3). For example, the appearance of a halo turn-off is apparently near $i = 17.5$, $(d - i) = 0.7$. Halo stars dominate the absolutely bright parts, and thick and thin disc stars dominate the intermediate and faint ones, respectively. In our model, we cannot distinguish the thick disc stars from the thin disc stars.

Most of the previous studies were based on the assumption of a suitable spatial density distribution, and on the observational luminosity function and colour–magnitude diagram for each stellar population, in order to fit the structural parameters and interpret them by simulating the distribution of colour and magnitudes (Gilmore & Reid 1983). Here, on account of the use of the photometric parallaxes, we can make a direct evaluation of the spatial density law. Rather than trying to fit the structure of the Galaxy in the observed parameter space of colour and magnitude, we transfer the observations into discrete density measurements at various points in the Galaxy.

In this study, the fields are located at intermediate and high latitudes, so neither a bulge component nor spiral arms are needed to describe the observation. The adopted model of stellar density distribution in this paper includes only two discs (a thin disc and a thick disc) and a halo. We try to derive the structural parameters (e.g. scale-height) of the thin and thick disc populations using our data set. For
Table 3. The colour–magnitude interval for the statistical discrimination of the disc and halo stars.

<table>
<thead>
<tr>
<th>Stellar populations</th>
<th>Disc</th>
<th>Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>(d−i)</td>
<td>(d−i)</td>
</tr>
<tr>
<td>(−17.5]</td>
<td>≥0.4</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>(17.5–18.5]</td>
<td>≥0.7</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>(18.5–19.5]</td>
<td>≥0.9</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>(19.5–20.5]</td>
<td>≥1.2</td>
<td>&lt;1.2</td>
</tr>
</tbody>
</table>

This, we calculate the stellar space density as a function of distance from the Galactic plane. At first, we use the two-dimensional distribution of stars in the (d−i) versus log r diagram (Fig. 5) to correct for this incompleteness. The nearest bins are assumed to be complete; for the incomplete bins we multiply iteratively by a factor given by the ratio of complete to incomplete number counts in the previous bin (Phleps et al. 2000). With the corrected number counts, the density in the log arithmetic space volume bins \( V_j \) can then be calculated according to

\[
\rho_j = \frac{N_j^{corr}}{V_j}, \tag{2}
\]

where \( V_j = (\pi/180)^2(\omega/3)(r_{j+1}^2 - r_j^2) \) is partial volume, \( r_{j+1} \) and \( r_j \) are the limiting distances and \( \omega \) is field size in square degrees.

4.1 Stellar density distribution in the disc

We have used a family of standard density laws to describe the populations of the Milky Way Galaxy. The disc structures are usually parametrized in cylindrical coordinates by a radial and vertical exponential,

\[
\rho(z, r) = \rho_0 e^{-z/h_1} e^{-(r-R_0)/h_2}, \tag{3}
\]

where \( z \) is vertical distance from the Galactic plane, \( x \) is the Galactocentric distance in the plane, \( R_0 \) is the solar distance to the Galactic Centre (8.5 kpc), \( \rho_0 \) is the normalized local density and \( h_1 \) and \( h_2 \) are the scaleheight and scalelength of the disc, respectively. A similar form uses the sech\(^2\) function to parametrize the vertical distribution:

\[
\rho(z, r) = \rho_0 \text{sech}^2 \left( \frac{-z}{z_0} \right) e^{-(r-R_0)/h_2}. \tag{4}
\]

A squared secans hyperbolicus is the sum of two exponentials. The functional form represents a self-gravitating isothermal disc, and it avoids a singularity at \( z = 0 \). Some studies show the sech\(^2\) fits better relative to the exponential density for faint absolute magnitude intervals for the thin disc in the optical star counts (Gould, Bahcall & Flynn 1996; Bilir, Karaali & Tuncel 2005). However, Hammersley et al. (1999) have shown that an exponential distribution, despite the singularity problems, is a much better fit to the infrared star counts of the Galaxy. In addition, Phleps et al. (2000) have shown that there is a only minor difference between the sech\(^2\) hyperbolicus and the exponential fit when the distance is less than 1 kpc. At large distances, the sech\(^2\) function approximates the observed exponential density profile. We have chosen to use the exponential functional form in this paper. As long as vertical direction is considered, the equation is as follows:

\[
\rho(z) = n_1 e^{-(z/h_1)} + n_2 e^{-(z/h_2)}, \tag{5}
\]

where \( h_1 \) and \( h_2 \) are the scaleheights of the thin and thick discs, respectively.
Figure 5. Spatial distribution of \((d-i)\), and the photometric distances are derived according to the stellar type.

Figure 6. Vertical density distribution of the disc stars in the four field as an example. The solid line is a fit with a superposition of two exponentials, and the dashed line is the single exponential fit for the thin disc component.

Fig. 6 shows the resulting density distribution of the disc stars in the four fields as an example. The solid line represents a fit with a superposition of two exponentials, and the dashed line is the fit for the thin disc component. The comparison between the data and models is made using a \(\chi^2\) fit. The most likely values for the thin disc scaleheight \(h_1\), the thick disc scaleheight \(h_2\) and the corresponding space number density normalization \(n_2/n_1\) are given in Table 4. Here, the thick disc density normalization is given in comparison to the density of the thin disc at the Sun. The errors of scaleheights and the corresponding space number density normalization are estimated at a 68 per cent confidence level. We find that the scaleheight is variable with the direction. The range of scaleheight for the thin
Disc varies from 220 to 320 pc. An old disc with an exponential scaleheight lower than the canonical value (325 pc) has been indicated by some authors such as Gilmore (1984), Bahcall & Soneira (1984) and Reid & Majewski (1993). Although 220 pc seems an extreme value, it is close to the lower limit in the literature. In addition, the range of thin disc scaleheight may be noisy resulting from the very few nearby stars which are sampled in high-latitude small fields. The range of scaleheight for the thick disc is from 600 to 1100 pc, and the corresponding space number density normalization is 7.0–1.0 per cent of the thin disc. At the same time, it shows that the thick disc dominates star counts at distances between 1.5 and 4 kpc over the galactic plane. In Table 4, it shows that the range of disc scaleheight and the normalization values found in a group of fields are very close to each other on the sky. This may be due due to the system noise.

Some results for the thin disc scaleheight have been published in the literature. For example, some authors (Bahcall & Soneira 1984; Gilmore 1984; Yoshii et al. 1987; Reid & Majewski 1993) derived a scaleheight of 325 pc for the old-disc stars; Chen et al. (2001) derived the scaleheight of the thin disc to be 330 pc using two large star count samples. However, Kuijken & Gilmore (1989) derived a scaleheight of 294 pc for the old-disc stars. Haywood (1994) showed, from an analysis of numerous star counts towards the pole using his self-consistent evolutionary model, that the thin disc scaleheight does not exceed 250 pc. Ojha et al. (1999) also found that the scaleheight of the thin disc is 240 pc based on an analysis of two star count samples. Siegel et al. (2002) gave apparent scaleheight $Z_{0, disc} = 280–350$ pc. Our result for the thin disc scaleheight is in a range of 220–320 pc. Karaali et al. (2004) showed that the thin disc scaleheight decreases from absolutely bright to faint stars in a range 265–495 pc. They discussed the large range of Galactic structure parameters and claimed that the Galactic model parameters are absolute-magnitude dependent (Bilir, Karaali & Gilmore 2006). It is clear that our derived thin disc scaleheight is close to the value presented by Siegel et al. (2002) and Karaali et al. (2004) from several selected areas. This is not a surprise, since most studies are based on the investigation of one or a few fields in different directions.

The thick disc vertical structure is generally described as exponential, with scaleheights varying between 480 and 1500 pc and its local density between 1 and 15 per cent relative to the thin disc. Because of the small proportion of the thick disc locally with regard to the thin disc, it is difficult to derive an accurate scaleheight or the local density of the thick disc. In general, any values of $h_z$ in the range 480–1500 pc and of local density in 1–15 per cent turn out to be acceptable (Robin et al. 1996). The thick disc’s scaleheight is anticorrelated with its local density when fitted simultaneously in star count analysis, and a small scaleheight is obtained in combination with high local density, while large scaleheight is associated with low local density (Robin et al. 1996).

In some studies, the range of the parameters is large especially for the thick disc. For example, Gilmore (1984) presented a scaleheight of 1300 pc and local normalization of 2 per cent, Kuijken & Gilmore (1989) derived a scaleheight of 1000 pc and local normalization of 4 per cent. Robin et al. (1996) used broad-band multicolour photometric and proper motion data to derive a scaleheight of $h_z = 760 \pm 50$ pc with a local density of $5.6 \pm 1$ per cent relative to the thin disc. Spagna, Lattanzio & Lasker (1996) used a $BVR$ star count and proper motion data towards the North Galactic Pole (NGP) to derive the scaleheight of $1137 \pm 61$ pc with a local density of 4.3 per cent. Ojha et al. (1999) presented a scaleheight of 790 pc with a local density of 6.1 per cent of the thin disc from a photometry and proper-motion survey in the two directions at intermediate latitude. Chen (2001) gave a thick disc scaleheight between 580 and 750 pc, with a local density of 13–6.5 per cent of the thin disc. Siegel et al. (2002) also investigated these parameters, matching their Galactic model against deep multicolour star count data for seven fields spanning a range of latitude and longitude. They derived a thick disc scaleheight of 740 pc with an 8.5 per cent normalization to the old disc. Our derived results in this work show the thick disc scaleheight of 600–1100 pc, with a corresponding density normalization of 7.0–1.0 per cent of the thin disc.

In summary, the scaleheights derived from various studies show large divergence, which cannot simply be attributed to statistical errors. There could be a number of reasons why the scaleheight varies with the observed direction in this study. The first reason could be from the photometric parallaxes uncertainty arising from either the misclassification or the metallicity correction. But, unless the parallax correction is incorrect, this would not produce the effects that we are seeing. The second possibility is that our adopted models assume the scaleheight is constant with radius from the Galactic Centre. However, maybe the disc (mainly the thick disc) is flared, with a scaleheight that increases with radius. This possibility is also mentioned in Siegel et al. (2002). In addition, it is clear that star counts when restricted to a small number of Galactic directions and a small magnitude range do not give a strong constraint on the scaleheight.

### 4.2 Stellar density distribution in the halo

Among all of the Galaxy’s populations, the halo is traditionally expected to have changed the least since it formed, and therefore it provides important clues to the Galaxy’s formation and evolution. The halo is not only less massive than the disc, but also it occupies a much larger volume than the disc (Larsen & Humphreys 2003). According to the studying for the photographic plates of nearby galaxies, there are numerous forms for the density law of spheroid components. The de Vaucouleurs law is most used to describe the

<table>
<thead>
<tr>
<th>Field name</th>
<th>Thin disc $h_z$ (pc)</th>
<th>Thick disc $h_z$ (pc)</th>
<th>Thick disc local normalization</th>
<th>Halo axis ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>T485</td>
<td>310 ± 17</td>
<td>930 ± 20</td>
<td>0.010</td>
<td>0.70</td>
</tr>
<tr>
<td>T518</td>
<td>220 ± 17</td>
<td>600 ± 15</td>
<td>0.026</td>
<td>0.37</td>
</tr>
<tr>
<td>T288</td>
<td>265 ± 20</td>
<td>810 ± 25</td>
<td>0.021</td>
<td>0.67</td>
</tr>
<tr>
<td>T477</td>
<td>280 ± 25</td>
<td>1020 ± 25</td>
<td>0.010</td>
<td>0.67</td>
</tr>
<tr>
<td>T328</td>
<td>245 ± 25</td>
<td>720 ± 15</td>
<td>0.030</td>
<td>0.46</td>
</tr>
<tr>
<td>T349</td>
<td>260 ± 16</td>
<td>600 ± 30</td>
<td>0.026</td>
<td>0.49</td>
</tr>
<tr>
<td>TA26</td>
<td>230 ± 17</td>
<td>690 ± 30</td>
<td>0.021</td>
<td>0.50</td>
</tr>
<tr>
<td>T291</td>
<td>290 ± 23</td>
<td>810 ± 25</td>
<td>0.019</td>
<td>0.58</td>
</tr>
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<td>305 ± 30</td>
<td>900 ± 30</td>
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<td>0.61</td>
</tr>
<tr>
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<td>320 ± 12</td>
<td>840 ± 30</td>
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<tr>
<td>U085</td>
<td>320 ± 15</td>
<td>780 ± 23</td>
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<tr>
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<td>810 ± 20</td>
<td>0.012</td>
<td>0.43</td>
</tr>
<tr>
<td>T491</td>
<td>270 ± 20</td>
<td>750 ± 30</td>
<td>0.032</td>
<td>0.40</td>
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<tr>
<td>T359</td>
<td>255 ± 30</td>
<td>600 ± 20</td>
<td>0.039</td>
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</tr>
<tr>
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<td>310 ± 19</td>
<td>1050 ± 30</td>
<td>0.024</td>
<td>0.64</td>
</tr>
<tr>
<td>T534</td>
<td>300 ± 20</td>
<td>720 ± 20</td>
<td>0.048</td>
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</tr>
<tr>
<td>T193</td>
<td>250 ± 30</td>
<td>600 ± 20</td>
<td>0.069</td>
<td>0.40</td>
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<tr>
<td>T516</td>
<td>240 ± 20</td>
<td>750 ± 25</td>
<td>0.028</td>
<td>0.50</td>
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<tr>
<td>T329</td>
<td>320 ± 15</td>
<td>640 ± 30</td>
<td>0.068</td>
<td>0.60</td>
</tr>
<tr>
<td>TA01</td>
<td>320 ± 20</td>
<td>960 ± 15</td>
<td>0.019</td>
<td>0.61</td>
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<tr>
<td>T517</td>
<td>220 ± 10</td>
<td>750 ± 30</td>
<td>0.010</td>
<td>0.44</td>
</tr>
</tbody>
</table>

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Galactic structure studies from BATC survey

Figure 7. Density distribution perpendicular to the Galactic plane, the dotted line shows the contribution of the thin disc component, the dashed line is the contribution of the thick disc, the dot–dashed line is a de Vaucouleurs law and the solid line is the sum of the three.

Surface brightness profile of elliptical galaxies. The de Vaucouleurs law is an empirical description of the density distribution of the Galactic halo. The analytic approximation is

\[
\rho_s(R, b, l) = \rho_0 \exp\left[-10.93(R/R_\odot)^{1/4} + 10.093\right] \\
\times 1.25 \frac{\exp[-10.93(R/R_\odot)^{1/4} + 10.093]}{(R/R_\odot)^{7/8}}, \quad R < 0.03 R_\odot \\
\times \left[1 - 0.08669 \left(\frac{R}{R_\odot}\right)^{1/4}\right], \quad R \geq 0.03 R_\odot. 
\]

where \(R = (x^2 + z^2/κ^2)^{1/2}\) is Galactocentric distance, \(κ\) is the axis ratio, \(x = (R^2_\odot + d^2 \cos^2 b - 2 R_\odot d \cos b \cos l)^{1/2}\), \(z = d \sin b\); \(R_\odot = 8\) kpc is the distance of the sun from the Galactic Centre, \(b\) and \(l\) are the Galactic latitude and longitude; the normalization factor \(\rho_0\) is usually expressed as a percentage of the local spatial density of stars.

Other models have used the power-law form,

\[
\rho_s(R) = \frac{\rho_0}{a_0^2 + R^2},\quad (7)
\]

where \(a_0\) is the core radius (an often omitted parameter).

Although Ng et al. (1997) claimed that a halo population described as a \(r^{1/4}\) law predicts less stars than power law at fainter magnitudes, the choice of halo density is somewhat arbitrary since the difference between de Vaucouleurs law and power law are subtle when seen through such a roughly ground lens as star counts. In our analysis, we use the blue stars (Table 3) to distinguish the population of halo stars from our sample stars. We adopted a de Vaucouleurs law for the halo component of the Galaxy and a local density normalization \(\rho_0 = 0.125\) per cent in the model. Fig. 7 gives the density distribution of all stars in the four fields as an example. The dotted line shows the contribution of the thin disc component; the dashed line is the contribution of the thick disc; the dot–dashed line is a de Vaucouleurs law and the solid line is the sum of the three components. It can also be seen that the corresponding plots fit the distribution of the halo stars up to a distance of over 15 kpc above the Galactic plane. Our counts imply that the axis ratio of the stellar halo varies from 0.4 to 0.7.

From our sample fields, T521, T491, T359, T193 and T534 should belong to the inner part of the halo, while the others lie in the outer part of the halo according to their longitude and latitude. The axis ratio versus the longitude distribution is shown in Fig. 8. It is clear that the axis ratio towards the Galactic Centre is somewhat flatter (\(\sim 0.4\)), while the shape of the halo in the anticentre and antirotation direction is rounder with \(c/a > 0.4\). For T518, the deviant result may reflect a fluctuation in the Galactic density distribution, or a systematic error in the observational data. Moreover, the scatter of the halo parameter may be related to the Sgr stream seen in the SDSS (Belokurov et al. 2006). The Sgr stream provides a probe of the shape of the Galactic halo. In summary, star counts in different lines of sight can be used directly to obtain a rough estimate of the...
shape of the stellar halo, although a dependency on models enters through isolating halo stars.

Besides, since our sample fields are not in the lower latitude areas, which were noted to have asymmetry (Larsen & Humphrey 1996; Newberg & Yanny 2005; Xu, Deng & Hu 2006), we cannot detect the triaxial halo distribution.

The apparent discrepancy of the halo axis ratio from various studies may be due to the multicomponent nature of the Galactic halo (Buser & Kaeser 1985). Hartwick (1987) found that the metal-poor globular clusters and RR Lyrae stars both had a spatial distribution that was better fitted by the two components; the inner component, which dominates in the solar neighborhood, is flattened with an axis ratio of \(c/a > 0.6\), while the outer component is spherical. Kinman, Suntzeff & Kraft (1994) also found evidence for two components, one significantly flattened which dominates locally, and one more spherical, in their sample of halo blue horizontal branch stars. Some studies of the kinematics and abundance of both field stars and globular clusters show that the halo is better described as having two subpopulations: a flattened inner halo and a spherical outer halo (Siegel et al. 2002). Additional support for dual-halo models can be drawn from the apparent dichotomy in the detailed chemical abundance of halo stars (Nissen & Schuster 1997). In a dual-halo model, the nearby stars (Wyse & Gilmore 1989; Larsen & Humphrey 1994; Siegel et al. 2002; Larsen & Humphreys 2003; Lemon et al. 2004, this work) are dominated by the flattened inner halo while the distant stars are dominated by the round outer halo (Bahcall & Soneira 1984; Koo, Kron & Courdworth 1986; Preston, Shectman & Beers 1991).

The principal contribution of star counts in constraining Galactic formation scenarios lies in revealing the underlying shape, chemistry and ages of the stellar population through sophisticated modeling. Our study of stellar halo provides some support for the hybrid formation model. The existence of two components may be the evidence that the stellar halo formed by hybrid collapse process (van den Bergh 1993; Zinn 1993; Norris 1994; Wyse 1995; Chiba & Beers 2000), or the stellar halo is locally flattened in response to the disc potential (Binney & May 1986), or perhaps reflects the different orbital parameters and the internal structure of disrupted satellite galaxies that were accreted by the Galaxy to form the stellar halo (Freeman 1987).

## 5 SUMMARY AND DISCUSSION

We have analysed the BATC survey data observed in 21 fields with the help of a Galaxy model in order to parametrize the vertical distribution of stars in the Milky Way. The adopted model of the Galaxy consists of three components: thin disc, thick disc (exponential form) and halo (de Vaucouleurs law). From the \(\chi^2\) fit to the direct measurement of the stellar density distribution, we determine that the range of scaleheight for the thin disc varies from 220 to 320 pc. Although 220 pc seems an extreme value, it is close to the lower limit in the literatures. The range of scaleheight for the thick disc is from 600 to 1100 pc, and the corresponding space number density normalization is \(7 \times 10^{-5}\) per cent of the thin disc. Our results show that the scaleheight is variable with the observation direction, which cannot be attributed to statistical errors. Possibly the main reasons can be attributed to the disc (mainly the thick disc) is flared, with a scaleheight that increases with radius. It is consistent with the merger origin for the thick disc formation. The actual numerical values of Galactic structure parameters are less scientifically important than what they tell us about the Galaxy in general – for example, the origin of the populations. A number of scenarios have been proposed for the origin of the thick disc (see review in Majewski 1993; Siegel et al. 2002).

In addition, by adopting a de Vaucouleurs \(r^{1/4}\) law halo and a local density normalization \(\rho_0 = 0.125\) per cent, we find that the axis ratio towards the Galactic Centre is more flatter (\(\sim 0.4\)), while the shape of the halo in the anticentre and antitrotation direction is rounder with \(c/a > 0.4\). It reflects the shape of the inner halo. In a word, the star counts in different lines of sight can be used directly to obtain a rough estimate of the shape of the stellar halo. With completeness limits for our selected fields typically from 19th to 21th magnitude, our star counts are most applicable to the inner halo. Our solutions support the Galactic models with a flattened inner halo. The inner halo is difficult to distinguish from the thick disc, and it is chemically and kinematically overlapped with the thick disc – possibly formed by an early merger in the Galaxy’s history. The outer halo is more or less spherical and is disjointed from the inner halo. In particular, the outer halo might be dominated by the substructures that are likely the remnants of interactions.

Evidence has been growing for some time that simple description of the Galactic halo is inadequate. It is possible that the axis ratio may vary with distance, and the halo becomes more spherical in the outer parts. Some surveys have also found a single axis ratio too restrictive and adopted an axis ratio \((c/a)\) that increases with Galactocentric radius to explain the stellar spatial distribution in the halo. The dual-halo models may resolve many of the disagreements in star count results. However, answering the question of whether or not the multicomponent or triaxial halo is supported requires more data such as kinematics and chemical abundances analysis. The question will be resolved with the coming on-line of future projects aimed at spectroscopic sky surveys such as SEGUE, LAMOST, GAIA and further photometric surveys of the southern sky.

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