# Star Counts and Galactic Structure *

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*We use a model of the Galactic stellar distribution to analyse the BATC star count data toward two high Galactic latitude fields. Since star counts at high Galactic latitudes are not strongly related to the radial distribution, they are very suitable for the study of the vertical distribution of the Galaxy. The vertical density distribution of the stars shows the contribution of the thin disc, the thick disc and the stellar halo of the Galaxy. We give quantitative descriptions of these components in terms of exponential discs and a de Vaucouleurs halo. We find that the observed counts support an axial ratio of* $c/a \sim 0.5$*, implying a more flattened halo. We consider that it is possible that the halo has two subpopulations, i.e. a flattened inner halo and a spherical outer halo in the Milky Way.*

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The detailed study of the Galactic structure enables us to address many important questions in astrophysics, for it is only in the Milky Way that we can make detailed studies that enable us to infer the distribution of dark matter, the star formation history of the Galaxy and the evolution of the Galactic spiral structure.[1-3] The method predominantly used to study the Galactic structure is star counts. Over the past decade considerable effort has been made to gain information on the structure of the Galaxy by the star count method. Our knowledge of details of the structure of the Milky Way, as inferred from star count data with colour information, is about to enter the next level of precision with the development of high-speed, high-precision measuring machines. This will, in turn, require the refinement of models of Galactic structure to fit parameters of the basic components of our Galactic star system.

Bahcall and Soneira[4] established the first self-consistent model by analysing star count data and derived that the old thin disc has a scale height of 325 pc, and that the halo can be represented by a deprojected de Vaucouleurs $r^{1/4}$ law. Bahcall and Soneira[5] showed that their two-major-component (thin-disc and spheroid) model for the distribution of stars in the Galaxy is in agreement with all the available data. However, Gilmore[6] pointed out that the star count data cannot be fitted much better by a two-component model, and proposed a Galaxy model with three populations: the halo, thin disc and thick disc. Many observations show that this thick disc is distinct from the thin disc and the halo. Using a de Vaucouleurs $r^{1/4}$ law spheroid, Bahcall and Soneira[5] found that this axial ratio is at least 0.8. However, Wyse and Gilmore[7] argued on the basis of star counts that the axial ratio for the stellar halo is much flatter than this canonical value and they obtained a very different ratio of 0.6. Based on star counts from the APS catalogue of the POSS, Larsen and Humphrey[8] gave a mean ratio of 0.5 implying $c/a \leq 0.5$ for the stellar halo.

Although the existence of both the disc and halo components seems to be well established, the spatial distribution of the Galactic components are not well determined and remain controversial due to different and conflicting results from modelling of star counts. To constrain the Galactic structure with more precision, the Beijing–Arizona–Taiwan–Connecticut (BATC) multicolour photometric survey provides new catalogues with accurate object classification. These catalogues are very useful in constraining the structure of the main components of the Galaxy. In this Letter, based on the BATC observation, we investigate the vertical distribution of stars in the Milky Way.

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 10000 Å. Observation is carried out with the 60/90 cm f/3 Schmidt Telescope, located at the Xinglong station. A Ford Aerospace 2048×2048 CCD camera with a 15 $\mu$m pixel size is mounted at the main focus of the Schmidt telescope. The field of view of the CCD is $58' \times 58'$ with a pixel scale of $1.7''$. The photometric system and data reduction are described in detail by Fan[9] and Zhou[10]

The BATC T516 field and TA01 field were observed in 15 and 14 intermediate band filters, respectively. The central coordinates of the fields are $\alpha_{2000} = 0^{\mathrm{h}}55^{\mathrm{m}}26.6^{\mathrm{s}}$, $\delta_{2000} = 0^{0}51'43.5''$ (Galactic

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coordinates: $l = 123.7°$, $b = -62°$) and $\alpha_{2000} = 0^{\rm h}15^{\rm m}8.98^{\rm s}$, $\delta_{2000} = -0^{0}13'50.1''$ (Galactic coordinates: $l = 134°$, $b = -62°$) for T516 and TA01 field, respectively. In general, the limiting magnitude of our photometry is about $20.0^{\rm m}$ with an error of about $0.1^{\rm m}$ in the BATC $i$ band. The central wavelength of filter $i$ is 665.6 nm and of the filter $d$ is 454 nm.

Each object could be classified according to their SED information constructed from the multicolour photometric catalogue. The observed colours of each object are compared with a colour library of known objects with the same photometric system. Because the two fields have been observed by the Sloan Digital Space Survey (SDSS) and each object type (stars–galaxies–QSO) has been given, we can directly make use of those stars to obtain star types according to the stellar spectra library. Details about the classification of stars are given by Du[11] After knowing the stellar type, the photometric parallaxes can be derived by estimating absolute stellar magnitudes. A variety of errors affect the determination of stellar distances. The first source of errors is from photometric uncertainty less than 0.1 mag in the BATC $i$ band; the second from the misclassification, but the misclassification should be small due to the multicolour photometry. For luminosity class V, types F–G–K, the absolute magnitude uncertainty is about 0.3 mag, and 0.8 or more for late M main sequence stars. The two fields are lie in high latitude, the influence of interstellar extinction in the distance calculation can be neglected.

On account of the use of the photometric parallaxes, we can make a direct evaluation of the spatial density law. In this Letter, we consider models with three major components: a thin disc and a thick disc, both with exponential density profiles, and a halo component, with a de Vaucouleurs profile. Given a reliable stellar sample, the next step is to differentiate between member stars of the disc and those of the halo population. Standard star-count models indicate that the colour-magnitude range could be used to separate roughly different populations of the Galaxy.[15] In Fig. 1, we show the colour distribution of our sample stars. From the figure, we can see that the thick disc and halo populations overlap in the range $(d-i) < 1.0$. Here we use the colour-magnitude intervals appropriate for statistical discrimination of stellar populations to separate the halo and disc stars. Figure 2 gives the colour-magnitude diagram for two fields down to the limiting magnitude, $i = 20$. We attempt to derive the structural parameters (e.g. scale height) of the thin and thick disc populations using our data set at high latitude. For this we calculate the stellar space density as a function of distance from the Galactic plane. First, we correct the incompleteness for the observed stars. The method about the completeness correction can be found by Du[11] With the corrected number counts, the density can then be calculated by

$$\rho_j = \frac{N_j^{\rm corr}}{V_j}, \tag{1}$$

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

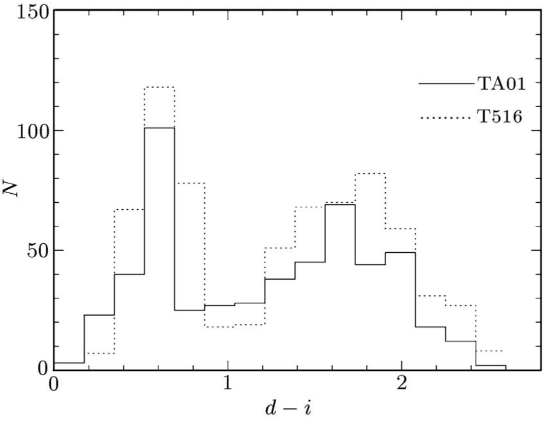

**Fig. 1.** Distribution of $(d-i)$ in the two fields.

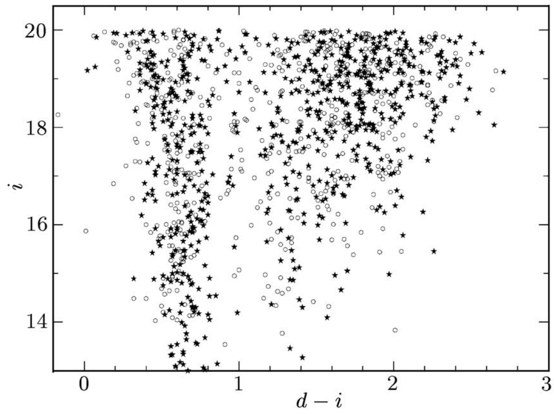

**Fig. 2.** Colour-magnitude diagram for two fields down to the limiting magnitude, $i = 20.$. The open circles represent the stars of TA01 field and the pentagons represent ones of T516 fields.

We study the distribution of the disc stars with exponential density profiles. The function of the disc density distribution is

$$\rho(z) = n_1 \exp(-z/h_1) + n_2 \exp(-z/h_2), \tag{2}$$

where $h_1$ and $h_2$ are the scale heights of the thin disc and thick disc. The comparison between data and simulations is made by using a $\chi^2$-fit. The corresponding parameters can be given. For T516 field, the scale height of the thin disc $h_1$ is $320^{+30}_{-24}$ pc, and the scale height of the thick disc $h_2$ is $720^{+120}_{-110}$ pc with a corresponding density normalization of $3.0 \pm 2\%$ with respect to the thin disc. For TA01 field, the scale height of the thin disc $h_1$ is $290^{+40}_{-30}$ pc, and the thick-disc scale height $h_2$ is $680^{+120}_{-100}$ pc, with a corresponding density normalization of 4.0 ± 3% with respect to the thin disc. The errors of scale heights and the corresponding space number density normalization are estimated at a 68% confidential level. We find that the results derived from two fields are consistent within the limits of errors.

Some results for the thin disc scale height have been published in the literature. Most authors derived a scale height of 325 pc for old-disc stars.[5,16] It is clear that our thin disc scale height derived is consistent with the classical value in the literature. The thick disc vertical structure is generally described as exponential profile with scale heights varying between 480 pc and 1500 pc and local density between 1% to 15% relative to the thin disc.[12] Because of the small proportion of the thick disc locally with regard to the thin disc, it is difficult to derive an accurate scale height and local density of the thick disc. In general, any values of $h_z$ in the range $480-1500$ pc and of local density in $1\%-15\%$ turn out to be acceptable. Robin [12] derived a scale height of $h_z = 760 \pm 50$ pc with a local density of $5.6 \pm 1.0\%$ with respect to the thin disc, and Ojha [13] presented a scale height of 790 pc with a local density of 6.1% of the thin disc from a photometry and proper-motion survey in the two directions at high latitude. By analysing the star with $M_v \geq +4$ near the south Galactic pole from the UK Schmidt Telescope, Gilmore [6] presented a scale height of 1300 pc and local normalization of 2%, and Rong and Buser [14] derived a scale height of 910 pc and a local density of 5.9%. Chen [15] gave a thick disc scale height between 580 pc and 750 pc, with a local density of 13–6.5% of the thin disc. It is clear that our results favour the thick disc scale height presented by Chen [15] well below the original proposal of Gilmore [6] The reason for this difference is mostly due to the extreme sensitivity of the model predictions to the colour range, the magnitude range and the direction of the adopted stellar sample. In addition, there is a slight correlation between scale height and local density when determined using star counts, and a small scale height is obtained in combination with high local density, while the large scale height is associated with the low local density.[12]

We use a de Vaucouleurs law for the halo component of the Galaxy. The de Vaucouleurs law is an empirical description of the density distribution of the Galactic halo. The analytic approximation is

$$\begin{aligned}\rho_H(z,b,l) &= \rho_0 \frac{\exp[-10.093(R/R_\odot)^{1/4}+10.093]}{(R/R_\odot)^{(7/8)}} \\ &\times 1.25\frac{\exp[-10.093(R/R_\odot)^{1/4}+10.093]}{(R/R_\odot)^{(6/8)}}, \\ &\quad R<0.03R_\odot \\ &\times [1-0.08669/(R/R_\odot)^{1/4}], \quad R\geq 0.03R_\odot,\end{aligned} \tag{3}$$

where $R = (x^2 + z^2/\kappa^2)^{1/2}$ is the galactocentric distance, $\kappa$ is the axis ratio, $x = (R_\odot^2 + d^2\cos^2 b - 2R_\odot d\cos b\cos l)^{1/2}$, $z = d\sin b$; $R_\odot = 8$ kpc is the distance of the sun from the Galactic centre, $b$ and $l$ are the Galactic latitude and longitude. Our counts imply that the axial ratio of the stellar halo approximates 0.5. This ratio agrees with the star count results of Larsen [8] and is also consistent with a kinematic analysis. 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, i.e. a flattened inner halo and a spherical outer halo.[17] Additional support for dual-halo models can be drawn from the apparent dichotomy in detailed chemical abundance of halo stars.[18] In a dual-halo model, nearby stars are dominated by the flattened inner halo while distant stars are dominated by the round outer halo. Such models may resolve many of the disagreements in star count results.

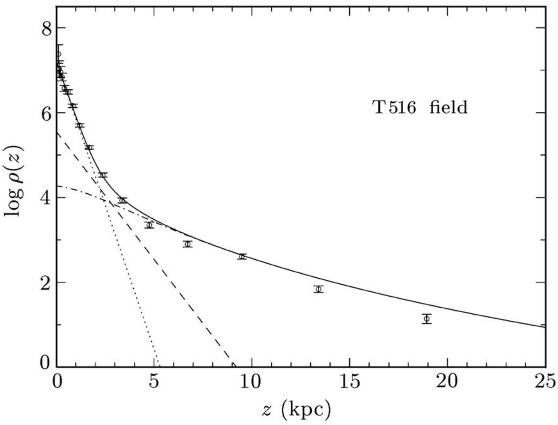

**Fig. 3**. Density distribution perpendicular to the Galactic plane in the T516 field: the dotted line shows the contribution of the thin disc component, the dashed line is the contribution of the thick disc, the dot-dashed line is a de Vaucouleurs law and the solid line the sum of the three.

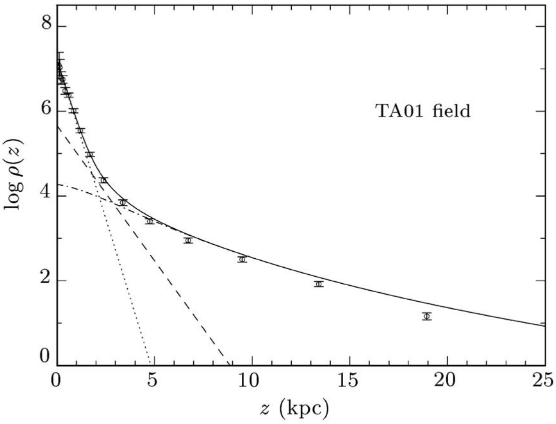

**Fig. 4**. As Fig. 3, but the density distribution are plotted for the TA01 field.

Figures 3 and 4 give the stellar density distribution in the BATC T516 and TA01 field. 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 Vaucouleus law, and the solid line is the sum of the three components. It is obvious that a single exponential disc is not a good fit for the disc component. The thick-disc components in our Galactic model is indispensable to explain the observed star counts. It shows that the thick disc dominates star counts at distances between 1.5 and 4 kpc over the Galactic plane. However, photometric counts are not accurate enough to estimate the distances of stars at the turnoff with an accuracy of even a factor of two. It can also be seen that the corresponding plots fit the distribution of the halo stars up to distance of over 20 kpc above the Galactic plane.

Based on the BATC observation, we have analysed the star counts with the help of a Galaxy model in order to parameterize the vertical distribution of stars in the Milky Way. Using two exponential discs, we determine that the scale height of the thin disc is $320^{+30}_{-24}$ pc and the thick-disc scale height is $720^{+120}_{-110}$ pc with a density normalization $3.0 \pm 2\%$ of the thin disc for the T516 field; the scale height of the thin disc is $290^{+40}_{-30}$ pc and the thick disc scale height is $680^{+120}_{-100}$ pc with a density normalization $4.0 \pm 3\%$ of the thin disc for the TA01 field. We derive the consistent results from the two fields. These results can provide a clue not only for the formation history of the thick disc, but also for the Galaxy as a whole. Adopting a de Vaucouleurs $r^{1/4}$ law halo and a local density normalization $\rho_0 = 0.125\%$, the observed counts in two fields yield a axial ratio of $c/a \sim 0.5$, implying a more flattened halo. Our study suggests that it is possible that the halo has two subpopulations, i.e. a flattened inner halo and a spherical outer halo in the Milky Way. Such a halo model might resolve many divergences in star count results. The axis ratio of the visible halo found in this paper is compatible with that of the dark halo,[19] suggesting that they have the same shape and dynamical origin.

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