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The Structure of the Galactic Halo *

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Abstract We used the star counts in 21 BATC fields obtained with the National Astronomical Observatories (NAOC) $60/90$ cm Schmidt Telescope to study the structure of the Galactic halo. Adopting a de Vaucouleurs $r^{1/4}$ law halo, we found that the halo is somewhat flatter ($c/a \sim 0.4$) towards the Galactic center than in the anticentre and antirotation direction ($c/a > 0.4$). We also notice that the axial ratios are smaller (flatter) towards the low latitude fields than the high latitude fields, except for a few fields. We provide robust limits on the large-scale flattening of the halo. Our analysis shows that the axial ratio of the halo may vary with distance and the observation direction. At large Galactocentric radii, the halo may not have a smooth density distribution, but rather, it may be largely composed of overlapping streams or substructures, which provides a support for the hybrid formation model.

Key words: Galaxy: structure — Galaxy: halo — Galaxy: fundamental parameters — Galaxy: formation

1 INTRODUCTION

The traditional star count analysis of the Galaxy has provided a picture of the basic structure and stellar populations of the Galaxy. The basic stellar components of the Galaxy comprise a thin disk, a thick disk, a central bulge and a halo, albeit that the inter-relationships and distinctions amongst the different components are still subject to some debate (Lemon et al. 2004). The canonical spatial density distribution is as follows: the stellar distributions for the thin disk and thick disk in cylindrical coordinates follow a radial and a vertical exponential law and that for the halo, the de Vaucouleurs spheroid (Du et al. 2003; Karaali et al. 2004). The structural parameters are deduced by comparing the theoretical model and the star count data. Tests on different parametrizations of the Galactic components have been carried out by many authors (Bahcall & Soneira 1980; Gilmore 1984; Ojha et al. 1996; Chen et al. 2001; Karaali et al. 2003, 2004, 2007; Du et al. 2003, 2006; Kaempf et al. 2005; Bilir et al. 2006a, 2006b, 2008; Cabrera et al. 2007; Brown et al. 2007).

However, due to different and conflicting results from the modeling of star counts, even the structural parameters of these major stellar components of the Galaxy have remained controversial. Now, it is highly important to quantify the stellar components of the Galaxy since they are closely related to stellar quantities such as distance, age, metallicity, and kinematics characteristics, that are necessary for understanding the formation and evolution of the Galaxy (Du et al. 2003, 2004b; Pohlen et al. 2004, 2007; Brook et al. 2005; Ivezic et al. 2008). For example, the flattening of the stellar halo, when combined with information on the metallicity and kinematics, can distinguish between models in which the halo formed with a little or a lot of gaseous dissipation, and so constrains the flattening of the dark matter halo. Constraints at the level of clustering in coordinate space, for the bulk of the stellar halo, are obviously important to recent tidal disruption of, and accretion of stars from, satellite stellar systems (Lemon et al. 2004). Among all the Galactic populations, the stellar halo is commonly expected to have changed the least since its formation,

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and so provides key clues to the Galactic formation and evolution. The halo is not only less massive than the disk, but also occupies a much larger volume than the disk (Larsen & Humphreys 2003). It is therefore of interest both as a record of the early history of the Galaxy and as a tracer of the Galactic potential.

Most previous investigations have focused on one or a few selected line-of-sight directions either in a small area to some great depth or over a large area to some shallower depths (e.g., Gilmore & Reid 1983; Bahcall & Soneira 1984; Reid et al. 1996). The deeper fields are small with correspondingly poor statistical weight, and the larger fields, limited by their shallower depth, may not be able to probe the Galaxy at large distance (Karaali et al. 2004). However, investigations of Galactic structure, such as quantifying the properties of the stellar components and substructure of the Galaxy, obviously benefit from large scale surveys. Moreover, 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 axial 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 disk stars, and those with a high axial ratio plus a high normalization (Peiris 2000).

The Beijing-Arizona-Taiwan-Connecticut (BATC) multi-color photometric survey covers 21 selected fields in various directions. From this catalogue and in conjunction with the Sloan Digital Space Survey-Date Release 4 (SDSS-DR4) reliable star counts are obtainable. The survey is restricted to medium and high latitudes, $|b| > 35°$, and is aimed at the structure of the Galactic stellar halo. Section 2 describes the observation data. Section 3 shows the star count model. Section 4 carries out a study of the halo flattening. Finally, a summary and discussion are given in Section 5.

2 OBSERVATIONS

The BATC survey carries out photometric observations with a large field, multi-colour system. There are 15 intermediate-band filters in the BATC filter system, which covers an optical wavelength range from 3000 to 10000 Å. 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 $58' \times 58'$ with a pixel scale of $1''.7$. The photometric system and data reduction are described in detail by Zhou et al. (2001)

In this paper, the BATC photometry survey covers 21 selected fields in various directions. Each field of view is ~ 1 deg^2. Table 1 lists the locations of the observed fields and their general characteristics. In the table, column 1 gives the BATC field name; columns 2 and 3, the right ascension (in hour, minute and second) and declination (in degree, arcminute and arcsecond); column 4 the epoch; columns 5 and 6, the Galactic longitude and latitude; and the last two columns the limit magnitude and the number of the sample stars in the field, respectively. As shown in column 7, most of our fields reach a depth of 21.0 mag in the i band. The selected fields provide a total of 29,800 main sequence stars with available multi-color data.

The fields used in this paper are towards the Galactic center, the anticentre, and the antirotation direction at median and high latitudes, $|b| > 35°$. The fields towards the anticentre and antirotation directions constrain the structure parameters in the outer part of the Galaxy, and the fields towards the Galactic center those in the inner part.

There are 15 intermediate-band filters covering the optical wavelength range from 3000 to 10 000 Å in the BATC multi-color system. Every object observed in all BATC fields can be classified according to their spectral energy distribution (SED). The selected fields have also been observed by the SDSS-DR4 and each object type (stars-galaxies-QSO) is given. Thus, we obtained our stellar catalogue. The probability of a given star belonging to a certain star class is computed by the SED fitting method. The observed colors of stars are compared with a color library of known stars on the same photometric system. The input library for stellar spectra is from Pickles (1998), which 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. The standard χ^2 minimization, i.e., computing and minimizing the deviations between photometric SED of a star and the template SEDs obtained with the same photometric system, is used in the fitting process. In this way we obtained the spectral types and luminosity classes for the stars in the BATC survey. After the stellar type is acquired, the photometric parallax can be derived by estimating the absolute stellar magnitude. Details of the method of stellar classification can be found in our previous papers (Du et al. 2003, 2004a, 2006).

Table 1 Observed Fields for this Study

Field name	R.A.	Decl.	epoch	l (deg)	b (deg)	i (Comp)	$N_{\rm stars}$
T485	8:38:02.00	44:58:38.0	1950	175.7	37.8	21.0	1687
T518	9:54:05.60	–0:13:24.4	1950	238.9	39.8	19.5	1389
T288	8:42:30.50	34:31:54.0	1950	189.0	37.5	20.0	1235
T477	8:45:48.00	45:01:17.0	1950	175.7	39.2	20.0	1103
T328	9:10:57.30	56:25:49.0	1950	160.3	41.9	19.5	878
T349	9:13:34.60	7:15:00.5	1950	224.1	35.3	20.5	1812
TA26	9:19:57.12	33:44:31.3	2000	191.1	44.4	20.0	1363
T291	9:32:00.30	50:06:42.0	1950	167.8	46.4	20.0	997
T362	10:47:55.40	4:46:49.0	1950	245.7	53.4	20.0	866
T330	11:58:02.90	46:35:29.0	1950	147.2	68.3	20.5	1031
U085	12:56:04.35	56:53:36.6	1996	121.6	60.2	21.0	1126
T521	21:39:19.48	0:11:54.5	1950	56.1	–36.8	20.5	2738
T491	22:14:36.10	–0:02:07.6	1950	62.9	–44.0	20.0	1837
T359	22:33:51.10	13:10:46.0	1950	79.7	–37.8	20.5	2401
T350	11:36:44.16	12:14:45.4	1950	251.3	67.3	19.5	749
T534	15:14:34.80	56:30:33.0	1950	91.6	51.1	21.0	1525
T193	21:55:34.00	0:46:13.0	1950	59.8	–39.7	20.0	2390
T516	0:52:50.08	0:34:52.6	1950	125.0	–62.0	20.0	1059
T329	9:53:13.30	47:49:00.0	1950	169.9	50.4	21.0	1441
TA01	0:46:26.60	20:29:23.0	2000	135.7	–62.1	20.5	1082
T517	3:51:43.04	0:10:01.6	1950	188.6	–38.2	20.0	1091

To obtain the Galactic structural parameters we calculate the stellar space density as a function of distance from the Galactic plane. First, we used the stellar distribution to correct the incompleteness (Phleps et al. 2000; Du et al. 2003). With the corrected number counts, the density in the log arithmetic space volume bins V_j can then be calculated with $\rho_j = \frac{N_j^{\rm corr}}{V_j}$. Here, $V_j = (\pi/180)^2(\omega/3)(r_{j+1}^3 - r_j^3)$ is the partial volume, r_{j+1} and r_j are the limiting distances, and ω is the field size in square degrees. The error of the corrected number counts can be derived according to the Poissonian error transformation (Phleps et al. 2000).

3 STAR COUNT MODEL

It is well known that the population type is a complex function of both color and apparent magnitude. Standard star count models indicate that different populations of the Galaxy can be roughly separated by ranges in the color-magnitude diagram. Figure 1 shows the $(d-i)$ color number distribution of the sample stars to be a bimodal one. The left-hand peak is dominated by the halo stars, while the one on the right is dominated by the thin disk stars, and the overlap between the two is dominated by the thick disk stars. Because the halo stars are far more distant than the bulk of the disk 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 colors. Besides, the halo stars are generally more metal poor, and hence tend to dominate the blue peak.

Most of the previous studies were based on the assumption of a suitable spatial density distribution, and on the observed luminosity function and color-magnitude diagram for each of the stellar populations, to fit the structural parameters and then to interpret them by simulating the distribution of color and magnitudes (Gilmore & Reid 1983). Here, thanks to 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 color and magnitudes, we transfer the observations into discrete density measurements at various points in the Galaxy.

To investigate the structure of the Galaxy from the stellar distribution along the line of sight, a theoretical model is needed. We adopt the model of stellar density distribution which includes only two disks (thin disk and thick disk) and a halo. We have chosen the exponential functional form for the thin disk and thick disk, and the de Vaucouleurs law for the stellar halo. To facilitate our determination of the flattening of the stellar halo, we held all the structural parameters fixed, except the stellar halo axial ratio. A local density normalization of $\rho_0 = 0.125\%$ is adopted for the halo. The parameters of the disks are taken from Du et al. (2006). The range of scale height for the thin disk varies from 220 to 320 pc, that for the thick disk, from

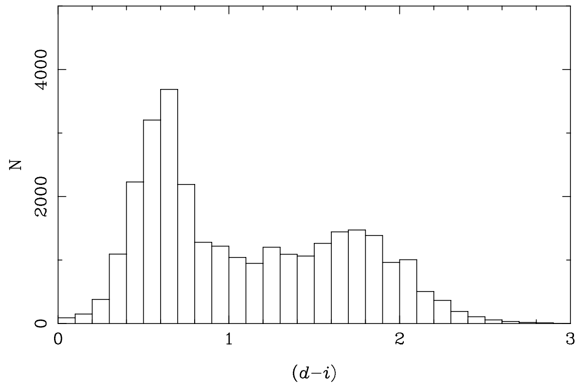

Fig. 1 Distribution of $(d-i)$ color number of the sample stars in the selected fields. Note the bimodal distribution.

600 to 1100 pc, and the corresponding space number density normalization is $7.0\% - 1.0\%$ of the thin disk. The scale height depends upon the observation direction.

4 HALO FLATTENING

According to previous results on the photographic plates of nearby galaxies, there are numerous forms for the density law of the spheroid component. It is generally modeled as by either a de Vaucouleurs law or a power law, $\rho(R) \propto R^{-n}$, with a flatted spheroid of axial ratio c/a. The de Vaucouleurs law is an empirical description of the density distribution of the Galactic halo, and it has been deprojected into three dimensions by Young (1976) as

$$\rho_s(R) = \rho_0 \exp[-7.669(R/R_e)^{1/4}]/(R/R_e)^{7/8}, \tag{1}$$

where $R = (x^2 + z^2/\kappa^2)^{1/2}$ is Galactocentric distance, κ is the axial ratio, $x = (R_\odot^2 + d^2\cos^2 b - 2R_\odot d \cos b \cos l)^{1/2}$, $z = d \sin b$; d the distance along the line of sight; $R_\odot = 8$ kpc the distance of the sun from the Galactic center, b and l are the Galactic latitude and longitude, R_e is the effective radius and the normalization factor ρ_0 is usually expressed as a percentage of the local spatial density of stars. Another form of the de Vaucouleurs profile is independent of the effective radius but is dependent on the solar distance from the Galactic center (Buser et al. 1995; Karaali et al. 2004):

$$\rho_s(R) = \rho_0 \exp[10.093(1 - R/R\odot)^{1/4}]/(R/R\odot)^{7/8}. \tag{2}$$

The choice of the halo density is rather arbitrary since the difference between the de Vaucouleurs and power laws is quite subtle, seen through such a roughly ground lens as star counts. We adopt a de Vaucouleurs law for the halo component of the Galaxy with a local density normalization $\rho_0 = 0.125\%$. Figure 2 shows the observed stellar density distribution and the theoretical model for two fields. It can be seen there is a good fit up to distance of over 15 kpc above the Galactic plane. Since the completeness limit for our fields is typically 19.5–21 magnitude in the blue, our star counts for the halo are applicable to most of the inner halo.

Of 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 axial ratio versus the longitude distribution is shown in Figure 3. It is clear that the halo (except field T518) is somewhat flatter (~ 0.4) towards the Galactic center and is rounder with $c/a > 0.4$ in the anticentre and antirotation directions. The axial ratio versus the latitude distribution is shown in Figure 4. We note that most of the axial ratios, with the exception of the T288, T477 and T485 fields, are flatter in the low latitude fields than in the high latitude fields. Table 2 gives the most likely numerical values of the axial ratio of the stellar halo in our studied fields. The results suggest that the axial ratio may vary with distance, becoming more spherical in the outer parts. It is clear that an oversimplified description for the Galactic halo using a single axial ratio throughout may be inadequate to explain the spatial distribution of the halo stars. The deviant

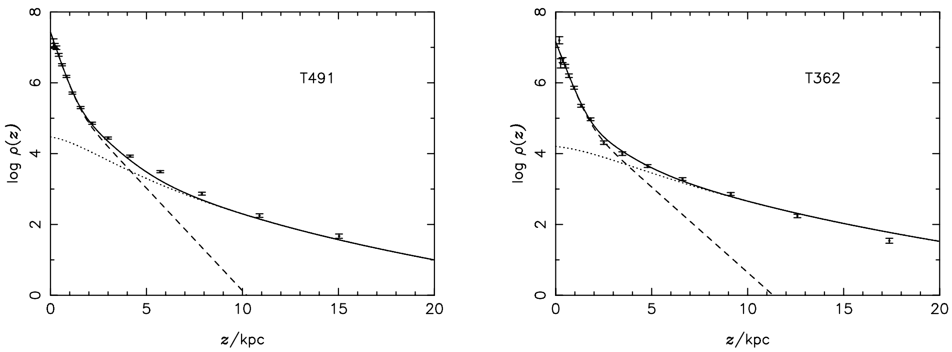

Fig. 2 Density distribution perpendicular to the Galactic plane in the two fields T491 and T362. The points with error bars represent the observational data with the estimated errors, the dashed line shows the contribution of the disk component, the dotted line is a de Vaucouleurs law and the solid line the sum of the two components.

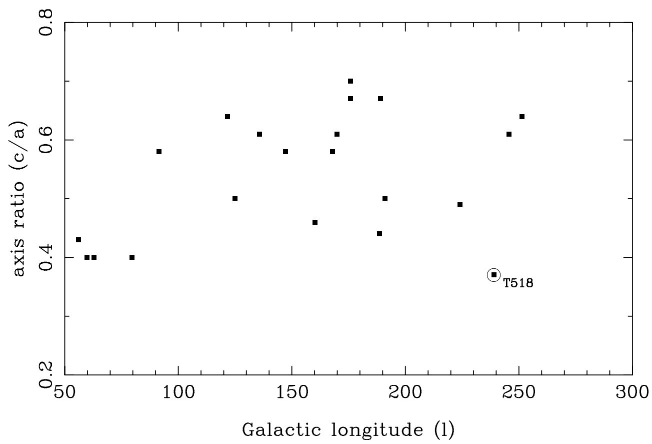

Fig. 3 Halo axial ratio versus Galactic longitude. Solid squares represent different observation fields and the open circle marks the abnormal T518 field.

behaviors of T518, T288, T477 and T485, probably reflect a fluctuation in the Galactic density distribution, or a systematic error in the observational data. Additionally, the presence of substructure and/or breaks in the halo can result in the scatter of the halo parameter. In fact, substructure in the halo has been directly observed among giant stars (Majewski et al. 2002), main sequence stars (Majewski et al. 1996; Newberg 2002; Dinescu et al. 2002) and blue horizontal branch/RR Lyrae stars (Yanny et al. 2000; Ivezic et al. 2000; Vivas et al. 2001). These results suggest that, at large Galactocentric radii, the halo may not have a smooth density distribution but may be largely or entirely comprised of overlapping streams.

Table 3 lists the results from recent studies. Apparent discrepancies from the various studies can be seen. In some reference, the axial ratio of the halo is absolute magnitude dependent (Karaali et al. 2004; Bilir et al. 2006). The samples cited here are at different distances, therefore include different contributions from the (flatter) inner halo and (rounder) outer halo (Reid 2005). Hartwick (1987) found that the metal-poor globular clusters and RR Lyrae stars both have a spatial distribution that is better fitted by two components: a flattened inner component and a spherical outer component. 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 subpopulation with a metallicity gradient and slow-rotation kinematics and a round outer subpopulation with no metallicity gradient and anisotropic kinematics (Zinn 1993; Dinescu et al. 1999; Siegel et al. 2002). Additional support for dual-halo models can be drawn from the apparent dichotomy in the detailed

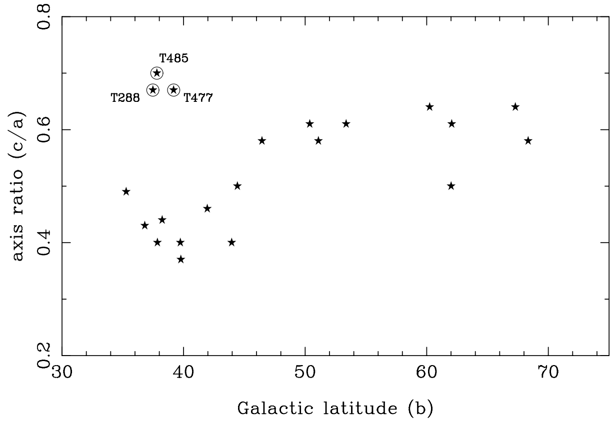

Fig. 4 Halo axial ratio versus Galactic latitude. The asterisks represent different observation fields, and open circles the three abnormal fields, T288, T477 and T485.

Table 2 Stellar Halo Axial Ratio in the Studied Fields

Field name	Longitude (l)	Latitude (b)	Axial ratio
T485	175.7	37.8	0.70
T518	238.9	39.8	0.37
T288	189.0	37.5	0.67
T477	175.7	39.2	0.67
T328	160.3	41.9	0.46
T349	224.1	35.3	0.49
TA26	191.1	44.4	0.50
T291	167.8	46.4	0.58
T362	245.7	53.4	0.61
T330	147.2	68.3	0.58
U085	121.6	60.2	0.64
T521	56.1	–36.8	0.43
T491	62.9	–44.0	0.40
T359	79.7	–37.8	0.40
T350	251.3	67.3	0.64
T534	91.6	51.1	0.58
T193	59.8	–39.7	0.40
T516	125.0	–62.0	0.50
T329	169.9	50.4	0.60
TA01	135.7	–62.1	0.61
T517	188.6	–38.2	0.44

chemical abundance of halo stars (Nissen & Schuster 1997). In a dual-halo model, the nearby stars (Larsen & Humphreys 1994, 2003; Siegel et al. 2002; Lemon et al. 2004) are dominated by the flattened inner halo while the distant stars are dominated by the round outer halo (Preston et al. 1991). The spherical outer halo may be composed of overlapping streams of stars and the smooth density distribution may only fit the inner Galaxy (Siegel et al. 2002). Thus, oversimplified descriptions for the Galactic halo are inadequate.

The principal contribution of star counts in constraining Galactic formation scenarios lies in revealing the underlying shape, chemistry and age of the stellar population through sophisticated modeling. The origin of the halo has been thought to be either through a rapid global collapse of the protogalactic gas cloud (ELS) or an accretion of protogalactic fragments (Searle & Zinn 1978). The accretion hypothesis is in line with the favored cold dark matter universe, which predicts a hierarchical clustering scenario of galaxy formation (White & Rees 1978; Navarro et al. 1997). Our study of stellar halo provides support for the hybrid formation model. The existence of multi-component may be evidence that the stellar halo formed by the hybrid collapse process (Wyse 1995; Van den Bergh 1993; Zinn 1993; Norris et al. 1994; Chiba &

Table 3 The Halo Density Distribution

Source	n	c/a	Comment
Sommer-Larsen & Zhen (1990)	3.3	0.55	Halo I, nearby stars
Sommer-Larsen & Zhen (1990)	3.3	0.85	Halo II, nearby stars
Yamagata & Yoshii (1992)	de Vaucouleurs	0.84	star counts
Larsen & Humphreys (1994)	de Vaucouleurs	0.48	star counts
Ng et al. (1997)	3.0	1.0	star counts
Robin, Reylé & Crézé (2000)	2.44	0.76	star counts
Chiba & Beers (2000)	3.55	1.0	nearby metal-poor stars
Chen et al. (2001)	2.5	0.55	star counts
Siegel et al. (2002)	2.5	0.6	star counts
Du et al. (2003)	de Vaucouleurs	0.6	star counts
Digby et al. (2003)	3.15	> 0.3	subdwarfs
Karaali et al. (2004)	de Vaucouleurs	0.7	star counts
Lemon et al. (2004)	de Vaucouleurs	0.56	star counts
Ak et al. (2007)	de Vaucouleurs	0.45	star counts

Beers 2000), or that the stellar halo is locally flattened in response to the disk potential (Binney & May 1986), or perhaps reflects different orbital parameters and internal structure of disrupted satellite galaxies that were captured by the Galaxy (Freeman 1987).

5 SUMMARY AND DISCUSSION

We used a sample of 29 800 main sequence stars from the BATC survey data observed in 21 fields to investigate the structure of the Galactic halo. We made a new estimation of the large-scale flattening of the halo. By adopting a de Vaucouleurs $r^{1/4}$ law halo and a local density normalization $\rho_0 = 0.125\%$, we found that the axial ratio towards the Galactic center is flatter (~ 0.4), while the shape of the halo in the anticentre and antirotation direction is rounder with $c/a > 0.4$. We also noticed that most of the axial ratios are rather flatter towards the low than high latitude fields, with exception of a few fields. We examined the reasons for the deviant results. These results suggest that the halo axial ratio may vary with distance and the observed direction, that, at large Galactocentric radii, the halo may not have a smooth density distribution but may be largely comprised of overlapping streams or substructures. Some surveys have also argued that a single axial ratio is too restrictive and adopted an axial ratio (c/a) that increases with Galactocentric radius to explain the stellar spatial distribution in the halo (Preston et al. 1991) that reflects the shape of the halo. 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 the completeness limits for our fields typically at blue magnitudes 19.5 to 21, our star counts for the halo are applicable to most part of the inner halo.

The actual numerical values of the Galactic structure parameters are less important than what they show us about the Galaxy in general, e.g., the origin of the populations. A number of scenarios have been proposed for the origin of the halo (see Siegel et al. 2002). Our study of stellar halo supports the hybrid formation model. The existence of multi-component may be evidence that the stellar halo formed by the hybrid collapse process, or perhaps reflects the internal structure of disrupted satellite galaxies, that the Galaxy accreted to form the stellar halo. The multi-component halo models may resolve many of the disagreements in the star count results. However, to answer the question whether the multi-component or triaxial halo is more suitable requires more work, such as analyses of kinematics and chemical abundance. The question will be resolved with the implementation of spectroscopic sky surveys, such as SEGUE, GAIA and LAMOST. In particular, the LAMOST survey will greatly increase the number of faint halo sources and will allow us to check the fine structure of the halo from the kinematics. Moreover, detailed chemical abundance investigations will help greatly in exploring the collision history of dwarf galaxies with the Galactic halo (Zhao et al. 2006).

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