The stellar metallicity distribution in intermediate-latitude fields with BATC and SDSS data

Xiyan Peng,† Cuihua Du†* and Zhenyu Wu‡

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

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ABSTRACT

Based on Beijing–Arizona–Taiwan–Connecticut (BATC) and Sloan Digital Sky Survey (SDSS) photometric data, we adopt the spectral energy distribution (SED) fitting method to evaluate the metallicity distribution for ~40 000 main-sequence stars in the Galaxy. According to the derived photometric metallicities of these sample stars, we find that the metallicity distribution shifts from metal-rich to metal-poor with the increase of distance from the Galactic Centre. The mean metallicity is about $-1.5 \pm 0.2$ dex in the outer halo and $-1.3 \pm 0.1$ dex in the inner halo and smoothly decreases from $-0.4$ to $-0.8$ in the interval $0 < r \leq 5$ kpc. A fluctuation in mean metallicity with Galactic longitude can be found in the interval $4 < r \leq 8$ kpc. There is a vertical abundance gradient $d[\text{Fe/H}]/dz \sim -0.21 \pm 0.05$ dex kpc$^{-1}$ for the thin disc ($z \leq 2$ kpc). At a distance $2 < z \leq 5$ kpc, where thick-disc stars dominate, the gradient is about $-0.16 \pm 0.06$ dex kpc$^{-1}$; this can be interpreted as a mixture of stellar populations with different mean metallicities at all $z$ levels. The vertical metallicity gradient is about $-0.05 \pm 0.04$ dex kpc$^{-1}$ for the halo ($z > 5$ kpc), so there is little or no metallicity gradient in the halo.

Key words: Galaxy: abundances – Galaxy: disc – Galaxy: formation – Galaxy: halo – Galaxy: stellar content – Galaxy: structure.

1 INTRODUCTION

The structure, formation and evolution of the Galaxy are very important issues in contemporary astrophysics. The basic components of the Galaxy are a thin disc, a thick disc, a halo and a central bulge, although the interrelationships among and distinction between different components remain subject to some debate (Gilmore & Reid 1983; Gilmore 1984; Lemon et al. 2004). Recent studies, based on accurate large-area surveys, have revealed that the Galaxy is marked by numerous irregular substructures such as the Sagittarius dwarf tidal stream in the halo (Ivezić et al. 2000; Yanny et al. 2000; Vivas et al. 2001; Majewski et al. 2003) and the Monoceros stream closer to the Galactic plane (Newberg et al. 2002; Rocha-Pinto et al. 2003). Carollo et al. (2007) showed that the halo stars are clearly divisible into two broadly overlapping structural components, an inner and an outer halo, from local kinematic analysis. It is now apparent that our Galaxy is a much more complex system than was thought before. The formation of galaxies was long thought to be a steady process resulting in a smooth distribution of stars (Bahcall & Soneira 1981; Gilmore, Wyse & Kuijken 1989; Majewski 1993). However, the view of formation of the Galaxy has changed dramatically since the discovery of complex substructures (Newberg et al. 2002; Belokurov et al. 2007). The presence of these lumpy and complex substructures is in qualitative agreement with models for the formation of the stellar halo through accretion and merging of nearby dwarf galaxies. Numerical simulations also suggest that this merger process plays a crucial role in setting the structure and motion of stars within galaxies (Bullock & Johnston 2005).

The abundance distribution is of particular importance in understanding the formation and chemical evolution of the Galaxy (Freeman & Bland-Hawthorn 2002). Researchers have long sought to constrain models for Galactic formation and evolution on the basis of observations of the stellar and cluster populations it contains. Specific models of galaxy formation make specific predictions about the stellar abundance distribution. For example, stars on more radial orbits are more metal-poor than stars on planar orbits. This may indicate that the formation of the Milky Way began with a relatively rapid collapse of the initial protogalactic cloud, which means that halo stars formed during the initial collapse while disc stars formed after the gas had settled into the Galactic plane. However, the global collapse theory was unable to account for the lack of an abundance gradient in the Galactic halo (Searle & Zinn 1978). The current view is that the Galactic halo formed at least partly through the accretion of small satellite galaxies or mergers of larger systems (Freeman & Bland-Hawthorn 2002), a theory that is well-supported by studies of stellar kinematics and spatial distributions (Yanny et al. 2003; Juric et al. 2008). The thick disc may be one of the most

*E-mail: ducuihua@gucas.ac.cn
significant components for studying the signatures of galaxy formation, because it presents a ‘snap’ frozen relic of the state of the early disc (Freeman & Bland-Hawthorn 2002). An intrinsic abundance gradient in the thick disc would favour scenarios in which the thick disc was formed either in the slow late stages of early Galactic collapse or through the gradual kinematic diffusion of disc stars. In contrast, an irregular metallicity distribution or absence of a gradient would favour the thick disc having formed via kinematic heating of the thin disc or from merger debris (Siegel, Karatas & Reid 2009).

The metallicity distribution of the Galaxy is best probed directly through spectroscopic surveys (Yoss, Neese & Hartkopf 1987; Allende-Prieto et al. 2006). However, it has the advantage of using the photometric metallicity is that many more metallicity of stars can be obtained. Accurate determination of the properties of Galactic components requires surveys with sufficient sky coverage to assess the overall geometry, sufficient depth for mapping stars to larger distances and sufficient information to obtain reasonable distance estimates for these stars (De Jong et al. 2010). Over the past few years, numerous surveys have been used to investigate the existence and size of the Galactic abundance gradient in the disc and halo. The existence of a radial gradient in the Galaxy is now well-established. An average gradient of about \(-0.06 \text{ dex kpc}^{-1}\) is observed in the Galactic disc for most elements (Chen, Hou & Wang 2003). De Jong et al. (2010) provided evidence for radial metallicity gradients in the Galactic stellar halo. However, there is considerable disagreement about whether there is a vertical metallicity gradient among field and/or open cluster stars of the Galaxy.

The Beijing–Arizona–Taiwan–Connecticut (BATC) multicolour photometric survey accumulated a large data base, which is very useful for studying Galactic structure and formation. Du et al. (2003) provided some information on the density distribution of the main components of the Galaxy, which can present constraints on the parameters of models of Galactic structure. Later, they used F and G dwarfs from the BATC data to study metal-abundance information (Du et al. 2004). With the new improved observations and improved knowledge regarding galaxy formation, it becomes possible to discuss further the metallicity gradient from different observation directions in the Galaxy.

In this paper, we attempt to study the metallicity gradient of the Milky Way galaxy using the 21 BATC photometric survey fields combined with Sloan Digital Sky Survey (SDSS) photometric data. The outline of this paper is as follows. The BATC photometric system and data reduction are introduced briefly in Section 2. In Section 3 we describe the theoretical model atmospheric spectra and synthetic photometry. The metallicity distribution is discussed in Section 4. Finally in Section 5 we summarize our main conclusions in this study.

2 OBSERVATIONS AND DATA

2.1 BATC photometric system and SDSS photometric system

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 3000–10 000 Å (Fan et al. 1996; Zhou et al. 2001). The 60/90-cm f/3 Schmidt camera of the National Astronomical Observatories (NAOC) was used in the BATC programme, 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 BATC magnitudes adopt the monochromatic AB magnitudes as defined by Oke & Gunn (1983). The PIPELINE II reduction procedure was performed on each single CCD frame to obtain the point-spread function (PSF) magnitude of each point source (Zhou et al. 2003). The detailed description of the BATC photometric system and flux calibration of the standard stars can be found in Fan et al. (1996) and Zhou et al. (2001, 2003). In order to apply more colour information to estimate the photometric stellar metallicity accurately, we combine the BATC colours with the SDSS colours for the sample stars.

The SDSS used a dedicated 2.5-m telescope, which has an imaging camera and a pair of spectrographs. The imaging camera (Gunn et al. 1998) contains 30 2048 × 2048 CCDs in the focal plane of the telescope. The flux densities of observed objects were measured almost simultaneously in five broad bands \([u, g, r, i, z]\) (Fukugita et al. 1996; Gunn et al. 1998; Hogg et al. 2001). To distinguish explicitly between BATC and SDSS filter names, we refer to the SDSS filters and magnitudes as \(u', g', r', i', z'\). The photometric pipeline (Lupton et al. 2001) detected the objects, matched the data from the five filters and measured instrumental fluxes, positions and shape parameters. The shape parameters allowed the classification of objects as point sources or extended. The magnitudes derived from fitting a PSF are currently accurate to about 2 per cent in \(g, r\) and \(i\) and 3–5 per cent in \(u\) and \(z\) for bright \((\leq 20\text{ mag})\) point sources. In Table 1, we list the parameters of the BATC and SDSS filters. Columns (1) and (2) represent the ID of the BATC and SDSS filters and columns (3) and (4) the central wavelengths and full width at half-maximum (FWHM) of the 20 filters, respectively. The reddening extinction for each star is determined from the SDSS catalogue.

### Table 1. Parameters of the BATC and SDSS filters.

| No. | Filter | Wavelength (Å) | FWHM (Å) |
|-----|--------|----------------|----------|
| 1   | \(a\)  | 3371.5         | 359      |
| 2   | \(b\)  | 3906.9         | 291      |
| 3   | \(c\)  | 4193.5         | 309      |
| 4   | \(d\)  | 4540.0         | 332      |
| 5   | \(e\)  | 4925.0         | 374      |
| 6   | \(f\)  | 5266.8         | 344      |
| 7   | \(g\)  | 5789.9         | 289      |
| 8   | \(h\)  | 6073.9         | 308      |
| 9   | \(i\)  | 6655.9         | 491      |
| 10  | \(j\)  | 7057.4         | 238      |
| 11  | \(k\)  | 7546.3         | 192      |
| 12  | \(m\)  | 8023.2         | 255      |
| 13  | \(n\)  | 8484.3         | 167      |
| 14  | \(o\)  | 9182.2         | 247      |
| 15  | \(p\)  | 9738.5         | 275      |
| 16  | \(q\)  | 3543           | 569      |
| 17  | \(r\)  | 4770           | 1378     |
| 18  | \(s\)  | 6231           | 1373     |
| 19  | \(t\)  | 7625           | 1526     |
| 20  | \(u\)  | 9134           | 9500     |
Table 2. Relative information for the BATC observation fields.

| Observed field | $l$ (deg) | $b$ (deg) | $i$ (Comp) | Star number |
|----------------|-----------|-----------|------------|-------------|
| T485           | 175.7     | 37.8      | 21.0       | 1550        |
| T518           | 238.9     | 39.8      | 19.5       | 1584        |
| T288           | 189.0     | 37.5      | 20.0       | 2115        |
| T477           | 175.7     | 39.2      | 20.0       | 2001        |
| T328           | 160.3     | 41.9      | 19.5       | 1666        |
| T349           | 224.1     | 35.3      | 20.5       | 2436        |
| TA26           | 191.1     | 44.4      | 20.0       | 1285        |
| T291           | 167.8     | 46.4      | 20.0       | 1670        |
| T362           | 245.7     | 53.4      | 20.0       | 1237        |
| T330           | 147.2     | 68.3      | 20.5       | 1020        |
| U085           | 121.6     | 60.2      | 21.0       | 1679        |
| T521           | 56.1      | 36.8      | 20.5       | 4430        |
| T491           | 62.9      | 44.0      | 20.0       | 2824        |
| T359           | 79.7      | 37.8      | 20.5       | 2932        |
| T350           | 251.3     | 67.3      | 19.5       | 1353        |
| T334           | 91.6      | 51.1      | 21.0       | 2044        |
| T193           | 59.8      | 39.7      | 20.0       | 2830        |
| T516           | 125.0     | 62.0      | 20.0       | 1113        |
| T329           | 169.9     | 50.4      | 21.0       | 1704        |
| TA01           | 135.7     | 62.1      | 20.5       | 1342        |
| T517           | 188.6     | 38.2      | 20.0       | 1296        |

The sample shows a main-sequence (MS) stellar locus but has significant contamination from giants, manifested in the broader distribution overlying the narrow stellar locus. In order to determine the MS star sample, we use the multicolour selection criteria outlined in Karaali et al. (2003a) and Juric et al. (2008), which remove objects based on their location relative to the dominant stellar locus. For example, Juric et al. (2008) applied an extra procedure which consists of rejecting objects at distances larger than 0.3 mag from the stellar locus in order to remove hot dwarfs, low-redshift quasars and white/red dwarf unresolved binaries from their sample. The procedure works well for high-latitude field data from SDSS (Karaali et al. 2003a; Yaz & Karaali 2010). Fig. 1(b) gives the cleaned sample stars after rejecting those objects that lay significantly off the stellar locus.

Figure 1. Two-colour diagrams for the BATC T329 field stars. Panel (a) is the distribution of sample stars in the $(j - m)/(g - j)$ two-colour diagram and panel (b) is the $(j - m)/(g - j)$ two-colour diagram after removing those objects that lay significantly off the stellar locus. The line denotes the stellar locus from equation (1).
characteristic of main sequences (log $g = 3.5$, 4.0, 4.5 for dwarfs) and 19 values of metallicity ([M/H] = $-5.0$, $-4.5$, $-4.0$, $-3.5$, $-3.0$, $-2.5$, $-2.0$, $-1.5$, $-1.0$, $-0.5$, $-0.3$, $-0.2$, $-0.1$, 0.0, 0.1, 0.2, 0.3, 0.5 and +1.0), where [M/H] denotes the metallicity relative to hydrogen. The synthetic $i$th filter magnitude can be calculated with equation (2):

$$m = -2.5 \log \left( \frac{\int F_i(\lambda) \, d\lambda}{\int \phi_i(\lambda) \, d\lambda} \right) - 48.60,$$

(2)

where $F_i$ is the flux per unit wavelength and $\phi_i$ is the transmission curve of the $i$th filter of the BATC or SDSS filter system (Du et al. 2004).

The bluer colours are sensitive to metallicity down to the lowest observed metallicities, because most of the line-blanking from heavy elements occurs in the shorter wavelength regions. In contrast, the redder colours are primarily sensitive to temperature index. The BATC $a$, $b$ bands contain the Balmer jump a stellar spectral feature that is sensitive to surface gravity. Since our sample includes only main sequences, it conveys little gravity information. It should be mentioned that although the metallicity or temperature derived from synthetic photometry is not very accurate for a single star, and perhaps can be distorted by a poor point, it is meaningful for the statistical analysis of sample stars.

### 3.2 Metallicity and photometric parallax

The most accurate measurements of stellar metallicity are based on spectroscopic observation. Despite recent progress in the availability of stellar spectra [e.g. SDSS-III and the Radial Velocity Experiment (RAVE)], the stellar numbers detected in photometric surveys are much greater than those from spectroscopic observations, so photometric methods have also often been used to give stellar metallicities. For example, Sandage (1969) detailed a technique using $UBV$ photometry indices to measure approximate abundance. Karaaei et al. (2003b) evaluated the metal abundance through the ultraviolet-excess photometric parameter using CCD $UBVI$ data. Karaaei, Bilir & Tuncel (2005) extended this method to the SDSS photometry. Ivezic et al. (2008) obtained the mean metallicity of stars as a function of $u - g$ and $g - r$ colours of SDSS data. For the BATC multicolour photometric system, there are 15 intermediate-band filters covering an optical wavelength range from 3000–10 000 Å. There are 5 filters for the SDSS photometric system, so the spectral energy distributions (SEDs) of 20 filters for every object are equivalent to a low-resolution spectrum.

The sample SED simulation with template SEDs can be used to derive the parameters of sample stars (Du et al. 2004). Standard minimization, computing and minimizing the deviations between the photometric SEDs of the star and the template SEDs obtained with the same photometric system, is used in the fitting process. The minimum indicates the best fit to the observed SED by the set of spectra (Du et al. 2004).

$$\chi^2 = \sum_{l=1}^{N_{\text{filt}}=20} \left( \frac{m_{\text{obs},l} - m_{\text{temp},l}}{\sigma_l} \right)^2,$$

(3)

where $m_{\text{obs},l}$, $m_{\text{temp},l}$ and $\sigma_l$ are the observed magnitude, template magnitude and their uncertainty in filter $l$, respectively, and $N_{\text{filt}}$ is the total number of filters in the photometry.

According to the results of SED fitting, the metallicity and temperature of about 40 000 sample stars are obtained in 21 fields. In addition, we extract the spectroscopic metallicities from the SDSS DR7 data base for our studied 21 fields, and there are about 870 stars for which there are also photometric metallicities from our method. Using these stars, we present a calibration of our SED-fitting method. After applying calibration, it is reliable for the derived photometric metallicities from the SED-fitting method. In Fig. 2, we present the difference of photometric and spectroscopic metallicity as a function of ($g - r$) colour. The uncertainties in the metallicity obtained from comparing SEDs from photometry and theoretical models are due to the observational error and the finite grid of the models. For metal-poor stars ([Fe/H] $< -1.0$) the metallicity uncertainty is about 0.5 dex, while it is 0.2 dex for stars with [Fe/H] $> -0.5$ (Du et al. 2004). The metallicity distribution diagram for all sample stars was given in Fig. 3. One local maximum appeared at [Fe/H] from $-0.5$ to 0 dex and a tail is visible down to $-3.0$ dex.

The stellar type can be derived from the effective temperature of dwarfs; then the stellar distance relative to the Sun can be obtained by equation (4):

$$m_v - M_v = 5 \log r - 5 + A_v,$$

(4)

where $m_v$ is the visual magnitude and absolute magnitude $M_v$ can be obtained according to the stellar type. The reddening extinction $A_v$ is small for most fields. We adopted the absolute magnitude versus stellar-type relation for main-sequence stars from Lang (1992). $r$ is the stellar distance. The vertical distance of the star to the Galactic
plane can be evaluated by equation (5):
\[ z = r \sin b. \]  

(5)

A variety of errors affect the determination of stellar distances. The first source of errors is from photometric uncertainties less than 0.1 mag in the BATC \( i \) band, the second from misclassification, which should be small due to the multicolour photometry. For luminosity class \( V \), types F/G, the absolute magnitude uncertainty is about 0.3 mag. In addition, there may exist an error from the contamination of binary stars in our sample. We neglect the effect of binary contamination on distance derivation due to the unknown but small influence from the mass distribution in binary components (Kroupa, Tout & Gilmore 1993; Ojha et al. 1996).

4 METALLICITY DISTRIBUTION

It is well known that the chemical abundance of a stellar population contains much information about the population’s early evolution. The stellar metallicity distribution in the Galaxy has been the subject of photometric and spectroscopic surveys (Gilmore & Wyse 1985; Ratnatunga & Freeman 1989; Friel 1988). In this study, we want to explore the possible stellar metallicity distribution variation with observation direction. A method of SED combination for the SDSS and BATC photometries has been adopted to give the stellar metallicity distribution. First, the metallicity for the sample stars can be derived by comparing SEDs between photometry and theoretical models. The SED-fitting method is described in Section 3.2. The mean metallicity distribution for each field is determined in the following distance intervals (in kpc): \( 15 < r \leq 20 \), \( 10 < r \leq 15 \), \( 8 < r \leq 10 \), \( 6 < r \leq 8 \), \( 5 < r \leq 6 \), \( 4 < r \leq 5 \), \( 3 < r \leq 4 \), \( 2.5 < r \leq 3 \), \( 2 < r \leq 2.5 \), \( 1.5 < r \leq 2 \), \( 1 < r \leq 1.5 \), \( 0.25 < r \leq 1 \). As an example the metallicity distribution as a function of vertical distance for the field T291 is presented in Fig. 4. From this figure, it is clear that there is a number shift from metal-rich stars to metal-poor ones with increasing distance. In star counts, the younger metal-rich stars are confined to regions close to the Galactic mid-plane while the older, metal-poorer stars with a larger scaleheight dominate at larger vertical distances from the Galactic plane.

![Graphs showing metallicity distribution](https://example.com/graphs.png)

**Figure 4.** The metallicity distribution for the T291 field over different distance ranges. At small distances, \( r < 1 \) kpc, most stars are in the range \([0, -0.5]\); at larger distances, \( 15 < r < 20 \) kpc, most stars are poorer than \(-1\).
4.1 Metallicity variation with Galactic longitude

Mean metallicity distributions as a function of Galactic longitude for different distance intervals are presented in Fig. 5. The mean metallicity shift from metal-rich to metal-poor with the increase of distance from the Galactic Centre can be found in Fig. 5. The solid points represent the south galactic latitude fields, the open square points represent the north galactic latitude fields. As shown in Fig. 5, the mean metallicity in interval \(10 < r \leq 20\) kpc is around \(-1.5\) dex. In interval \(8 < r \leq 10\) kpc our result indicates that the mean metallicity is \(-1.3\). The mean metallicity in interval \(5 < r \leq 8\) kpc is about \(-1.0\) and smoothly decreases from \(-0.6\) to \(-0.8\) in interval \(2.5 < r \leq 5\) kpc. Our results are consistent with the results of Siegel et al. (2009) and Karatas et al. (2009). Siegel et al. (2009) find a monometallic thick disc and halo with abundances of \([\text{Fe/H}] = -0.8\) and \(-1.4\) respectively. Karatas et al. derive mean abundance values of \([\text{Fe/H}] = -0.77 \pm 0.36\) dex for the thick disc and \([\text{Fe/H}] = -1.42 \pm 0.98\) for the halo. The mean metallicity decreases from \(-0.4\) to \(-0.6\) in interval \(0 < r \leq 2.5\) kpc. The mean metallicity in interval \(0.25 < r \leq 1\) kpc is \([\text{Fe/H}] \sim -0.3\), which is consistent with the result of Yaz & Karaali (2010).

As shown in Fig. 5, at larger distances \(r > 10\) kpc, compared with the typical error bars the mean metallicity distribution variation with Galactic longitude is almost flat. For \(4 < r \leq 8\) kpc, there is a fluctuation in the mean metallicity with Galactic longitude. The overall distribution of mean metallicity has a maximum at \(l \sim 200^\circ\). For \(2 < r \leq 8\) kpc, the T517 field (Galactic coordinates \(l = 188.6, b = -38.2\); equatorial coordinates \(\alpha = 58.59, \delta = -0.35\)) and the TA26 field (Galactic coordinates \(l = 191.1, b = 44.4\); equatorial coordinates \(\alpha = 139.956, \delta = 33.745\)) show a metal-rich character related to other fields. This feature may reflect a fluctuation from streams (such as the Monoceros stream) that are accreted from nearby galaxies. Juric et al. (2008) detect two overdensities in the thick-disc region. Klement et al. (2009) also find individual streams from the SEGUE Stellar Parameter Pipeline in the direction with central coordinates (equatorial coordinates \(\alpha = 58.58\) and \(\delta = -4.99\)). Perhaps the deviant behaviour of the two fields results from systematic errors in the observations. AK et al. (2007b) find that the metallicity distributions for both (relatively) short and long vertical distances show systematic fluctuations. The scaleheight of the thick disc varies with the observed direction which was found in the works of Du et al. (2006) and Bilir et al. (2008).

4.2 The vertical metallicity gradient

Detailed information about the vertical metallicity gradient can provide important clues about the formation scenario of stellar populations. Here, we used the mean metallicity to describe the
Figure 6. The mean metallicity as a function of vertical distance $z$ for the T291 field. The metallicity gradients of the thin disc, thick disc and halo are $-0.23 \pm 0.03$, $-0.18 \pm 0.07$, and $-0.05 \pm 0.01$ dex kpc$^{-1}$, respectively.

metallicity distribution function. As an example, the distribution trend of mean metallicity [Fe/H] with height above the Galactic plane [$z$] for the T291 field is shown in Fig. 6. The metallicity gradients for all the fields in different $z$ intervals $z < 2$ kpc, $2 < z \leq 5$ kpc and $5 < z \leq 15$ kpc are given in Fig. 7 and detailed in Table 3. In Table 3, column 1 represents the BATC field name, while columns 2–7 represent gradient and error of gradient in different $z$ ranges: $z \leq 2$ kpc, $2 < z \leq 5$ kpc and $5 < z \leq 15$ kpc, respectively.

From Fig. 7 we find that the variation of the gradient for the halo with Galactic longitude is flat and the mean gradient of the halo is about $-0.05 \pm 0.04$ dex kpc$^{-1}$ ($5 < z \leq 15$ kpc), which is essentially in agreement with the conclusions of Yaz & Karaali (2010) and Du et al. (2004). Du et al. (2004) find small or zero gradient $d[Fe/H]/dz = -0.06 \pm 0.09$ in the halo. Yaz & Karaali (2010) find $d[M/H]/dz = -0.01$ dex kpc$^{-1}$ for the inner spheroid. The result of Karaali et al. (2003a) is slightly steeper than our result. Karaali et al. (2003a) find that there is a metallicity gradient of $d[Fe/H]/dz \sim -0.1$ dex kpc$^{-1}$ in the inner halo ($5 < z \leq 8$ kpc) and zero in the outer part ($8 < z \leq 10$ kpc). From Fig. 6 we find that the incompleteness of the star sample causes significant statistical uncertainties at large distances. Probably there is little or no metallicity gradient in the halo. This is consistent with a merger or accretion origin of the outer halo.

As shown in Fig. 7, at distances $0 < z < 2$ kpc the mean vertical abundance gradient is about $d[Fe/H]/dz \sim -0.21 \pm 0.05$ dex kpc$^{-1}$. The value for the vertical metallicity at distances $0 < z < 2$ kpc is in agreement with the canonical metallicity gradients for the same $z$ distances. For example, Yaz & Karaali (2010) find that the metallicity gradient is $d[Fe/H]/dz \sim -0.3$ dex kpc$^{-1}$ for short distances. The metallicity gradient is found to be $d[Fe/H]/dz \sim -0.37$ dex kpc$^{-1}$ for $z < 4$ kpc in the work of Du et al. (2004). The result of Karaali et al. (2003a) can be described as $d[Fe/H]/dz \sim -0.2$ dex kpc$^{-1}$ for both thin and thick discs.

At distances $2 < z \leq 5$ kpc, where thick-disc stars dominate, the gradient is about $-0.16 \pm 0.06$ dex kpc$^{-1}$ in our work, which is consistent with the work of Karaali et al. (2003a) and less than the value of Du et al. (2004). Du et al. (2004) state that the metallicity gradient is $d[Fe/H]/dz \sim -0.37$ dex kpc$^{-1}$. In our study, the thick-disc gradient is interpreted as the result of different contributions from three components of the Galaxy at different $z$ distances. The existence of a clear vertical metallicity of the thick disc would be an important clue about the origin of the thick disc. However, the formation of the thick-disc component is an open question. A number of models have been put forward since the confirmation of its existence. Chen et al. (2001) support the suggestion that the thick disc formed through the heating of a preexisting thin disc, with the heating mechanism being the merging of a satellite galaxy. Here, we also favour the thick disc having formed via kinematic heating of the thin disc and from merger debris. Thus, there is an irregular metallicity distribution or absence of an intrinsic gradient.

Figure 7. The metallicity-gradient distributions for all fields in this study are shown for the intervals $z < 2$ kpc, $2 < z < 5$ kpc and $5 < z < 15$ kpc.

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5 CONCLUSIONS AND SUMMARY

In this work, based on the BATC and SDSS photometric data, we evaluated the stellar metallicity distribution for 40,000 main-sequence stars in the Galaxy by adopting an SED-fitting method. These selected fields are towards the Galactic Centre, antecentre and antirotation direction at median and high latitudes. The metallicity distribution could be obtained up to distances \( r = 20 \) kpc, which covers the thin disc, thick disc and halo. We determined the mean stellar metallicity as a function of vertical distance in different directions. It can be clearly seen that the metallicity distribution shifts from metal-rich to metal-poor with the increase of distance from the Galactic Centre. The mean metallicity is about \(-1.5 \pm 0.2\) dex in interval \( 10 < r \leq 20 \) kpc and \(-1.3 \pm 0.1\) dex in interval \( 8 < r \leq 10\) kpc. It smoothly decreases from \(-0.6\) to \(-0.8\) in interval \( 2.5 < r \leq 5\) kpc, while it decreases from \(-0.4\) to \(-0.6\) in interval \( 0 < r \leq 2.5\) kpc. In addition, a fluctuation in the mean metallicity with Galactic longitude can be found and the overall distribution has a maximum at about \( l \sim 200^\circ\) in interval \( 4 < r \leq 8\) kpc. Maybe this feature can be related to the substructure or streams (such as the Monoceros stream) that are accreted from nearby galaxies. At the same time, we find that the vertical abundance gradient for the thin disc (\( 0 < z < 2\) kpc) is \( d[\text{Fe/H}]/dz \sim -0.21 \pm 0.05 \) dex kpc\(^{-1}\), while the vertical gradient is \(-0.16 \pm 0.06\) dex kpc\(^{-1}\) at distances \( 2 < z \leq 5\) kpc where thick-disc stars dominate. Here, we consider that the thick-disc gradient may be the result of different contributions from three components of the Galaxy at different \( z\) distances. The vertical gradient \( d[\text{Fe/H}]/dz \sim -0.05 \pm 0.04\) dex kpc\(^{-1}\) is found for distance \( 5 < z \leq 15\) kpc. Thus, there is little or no gradient in the halo. These results are in agreement with the values in the literature (Yoss et al. 1987; Trefzger, Pel & Gabi 1995; Karai et al. 2003a; AK et al. 2007a; Yaz & Karai 2010). It is possible that additional observational investigations (some projects aimed at spectroscopic sky surveys such as SEGUE, LAMOST, GAIA) will give more evidence for the metallicity gradient of the Galaxy and therefore provide a powerful clue to disc and halo formation.

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| Table 3. The gradient distribution for different distance intervals for the selected fields. |
|---------------------------------|---------|--------|---------|--------|---------|--------|
| **Observed field**             | **0–2 (kpc) Gradient Error** | **2–5 (kpc) Gradient Error** | **5–15 (kpc) Gradient Error** |
| T193                            | -0.136 0.017                  | -0.080 0.020                  | -0.020 0.022                  |
| T288                            | -0.258 0.027                  | -0.267 0.032                  | -0.007 0.037                  |
| T291                            | -0.228 0.028                  | -0.185 0.071                  | -0.045 0.014                  |
| T328                            | -0.110 0.027                  | -0.126 0.032                  | -0.137 0.043                  |
| T329                            | -0.170 0.028                  | -0.100 0.042                  | -0.037 0.015                  |
| T330                            | -0.171 0.042                  | -0.217 0.055                  | -0.080 0.010                  |
| T349                            | -0.180 0.017                  | -0.225 0.050                  | -0.029 0.031                  |
| T350                            | -0.267 0.033                  | -0.178 0.074                  | -0.069 0.035                  |
| T359                            | -0.203 0.017                  | -0.126 0.023                  | -0.054 0.023                  |
| T362                            | -0.237 0.037                  | -0.126 0.060                  | -0.037 0.022                  |
| T477                            | -0.181 0.025                  | -0.275 0.030                  | -0.053 0.022                  |
| T485                            | -0.247 0.033                  | -0.119 0.044                  | 0.028 0.040                   |
| T516                            | -0.194 0.017                  | -0.179 0.020                  | -0.070 0.027                  |
| T517                            | -0.291 0.039                  | -0.204 0.061                  | -0.005 0.026                  |
| T518                            | -0.163 0.035                  | -0.026 0.045                  | -0.051 0.052                  |
| T521                            | -0.197 0.012                  | -0.175 0.013                  | -0.045 0.011                  |
| T534                            | -0.254 0.028                  | -0.110 0.035                  | -0.035 0.012                  |
| TA01                            | -0.199 0.037                  | -0.192 0.046                  | -0.047 0.015                  |
| TA26                            | 0.307 0.030                   | -0.187 0.038                  | -0.085 0.047                  |
| U085                            | -0.146 0.024                  | -0.148 0.037                  | -0.035 0.013                  |

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