A MONTE CARLO METHOD FOR MAKING THE SDSS u-BAND MAGNITUDE MORE ACCURATE

JIAYIN GU1, CUIHUA DU2, WENBO ZUO3, YINGJIE JING2, ZHENYU WU3, JUN MA3, AND XU ZHOU3

1 Department of Physics, Wuhan University of Technology, Wuhan 430000, People’s Republic of China; gujiayin12@mails.uac.ac.cn
2 School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China; ducihua@ucas.ac.cn
3 Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China

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Abstract

We develop a new Monte Carlo-based method to convert the Sloan Digital Sky Survey (SDSS) u-band magnitude to the south Galactic Cap of the u-band Sky Survey (SCUSS) u-band magnitude. Due to the increased accuracy of SCUSS u-band measurements, the converted u-band magnitude becomes more accurate compared with the original SDSS u-band magnitude, in particular at the faint end. The average u-magnitude error (for both SDSS and SCUSS) of numerous main-sequence stars with 0.2 < g − r < 0.8 increases as the g-band magnitude becomes fainter. When g = 19.5, the average magnitude error of the SDSS u is 0.11. When g = 20.5, the average SDSS u error rises to 0.22. However, at this magnitude, the average magnitude error of the SCUSS u is just half as much as that of the SDSS u. The SDSS u-band magnitudes of main-sequence stars with 0.2 < g − r < 0.8 and 18.5 < g < 20.5 are converted, therefore the maximum average error of the converted u-band magnitudes is 0.11. The potential application of this conversion is to derive a more accurate photometric metallicity calibration from SDSS observations, especially for the more distant stars. Thus, we can explore stellar metallicity distributions either in the Galactic halo or some stream stars.

Key words: Galaxy: abundances – methods: data analysis – stars: fundamental parameters – stars: statistics

1. INTRODUCTION

It is an increasing perception that the Galactic halo system comprises at least two spatially overlapping components with different kinematics, metallicity and spatial distribution (Carollo et al. 2007, 2010; An et al. 2013, 2015). Chemical abundance is the direct observational ingredient in investigating the dual nature of the Galactic halo. Since the chemical abundance of stars has a strong effect on the emergent flux, especially at blue end, the natural endeavor is to recover the metal information from large photometric surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000). The advantage of photometric metallicity estimates is that information on the metallicity of large numbers of stars can be obtained.

Based on the SDSS ugriz photometry, Ivezić et al. (2008) used a polynomial-fitting method from spectroscopic calibration of de-reddened u − g and g − r colors to derive the photometric metallicity (see also Peng et al. 2012). However, due to the relatively large error of the SDSS u-band magnitude, only the metallicities [Fe/H] of stars brighter than g = 19.5 were obtained. Combining the more accurate SCUSS (Zhou et al. 2016) u-band photometry, SDSS g and r photometry, Gu et al. (2015) developed a three-order polynomial photometric metallicity estimator, in which the u-band magnitude can be used for faint magnitudes of g = 21. However, both the estimators developed by Ivezić et al. (2008) and Gu et al. (2015) based on polynomial-fitting have the intrinsic drawback that they cannot be extended to the metal-poor end. In order to solve this problem, Gu et al. (2016) (hereafter denoted as Paper I) devised a Monte Carlo method to estimate the stellar metallicity distribution function (MDF) which appears particularly accurate at both metal-rich and metal-poor ends. The natural step forward is to combine the SCUSS u and SDSS g, r photometry with the method introduced in Paper I to investigate the MDF of the Galactic halo stars. But only those stars in the south Galactic cap are surveyed by the SCUSS. How can we estimate the photometric metallicity distribution of faint stars (deep in the Galactic halo) in both the south and north hemisphere? This paper provides a new method to achieve this goal. Due to the fact that the SCUSS u is more accurate than the SDSS u, we convert the latter to the former using a Monte Carlo method, through which the converted u magnitude becomes as accurate as the SCUSS u magnitude.

We organize this paper as follows. In Section 2, we give a brief overview of the SDSS and SCUSS. The technical details for converting the SDSS u to the SCUSS u are presented in Section 3. Section 4 evaluates the effectiveness of this conversion. A discussion of the potential application of the conversion is given in Section 5.

2. SDSS AND SCUSS

The SDSS is a digital multi-filter imaging and spectroscopic redshift survey using a dedicated 2.5 m wide-angle optical telescope at Apache Point Observatory in New Mexico, USA (Gunn et al. 2006). It began operation in 2000, and now covers over 35% of the sky, with about 500 million photometrically surveyed objects and more than 3 million spectroscopically surveyed objects. Five bands (u, g, r, i, and z) are used to simultaneously measure the objects’ magnitude, with effective wavelengths of 3551, 4686, 6165, 7481, and 8931 Å respectively. The limit magnitudes of u, g, r, i, and z are 22.0, 22.2, 22.2, 21.3, and 20.5, respectively (Abazajian et al. 2004). The relative photometric calibration accuracy values for u, g, r, i, and z are 2%, 1%, 1%, 1% and 1%, respectively (Padmanabhan et al. 2008). Other technical details about the SDSS can be found on the SDSS website http://www.sdss3.org/, which also provides an interface for public data access.

The south Galactic Cap u-band Sky Survey (SCUSS) is an international cooperative project that is jointly undertaken by
the National Astronomical Observatories of China and Steward Observatory of University of Arizona. It utilizes the 2.3 m Bok telescope located on Kitt Peak to photometrically survey the stars in the south Galactic Cap in the \( u \) band with an effective wavelength of 3538 Å. This project started in the summer of 2009, began its observation in the fall of 2010, completed in the fall of 2013, and finally about 5000 deg\(^2\) area (\( 30^\circ < l < 210^\circ, \, -80^\circ < b < -20^\circ \)) were surveyed. Its main goal is to provide the essential input data to the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) project (Zhao et al. 2006). Figure 1 shows the similarity in response curve between the \( u \) band filter of the SCUSS and that of the SDSS. The limit magnitude for point sources is about 23.2 mag with a 5 minute exposure time, and is about 1.5 mag deeper than that of the SDSS \( u \) band limit magnitude (Jia et al. 2014; Peng et al. 2015). In Table 1, we provide a brief summary of the SCUSS. More detailed information and data reduction about SCUSS can be found in Zhou et al. (2016), Zou et al. (2015, 2016), and the SCUSS website http://batc.bao.ac.cn/Uband/, which also provides an interface for public data access.

In Figure 2, the average errors of the SCUSS \( u \) and SDSS \( u \) of numerous main-sequence stars with \( 0.2 < g - r < 0.8 \) are plotted as functions of \( g \)-band magnitude. The figure clearly shows that the error of the SDSS \( u \) is much larger than that of the SCUSS \( u \) on the whole, especially at the faint end. The spectroscopically surveyed stars have limiting magnitude of \( g = 19.5 \). Coincidentally, the error of the SDSS \( u \) limits the application of photometric metallicity estimates in the range of \( g < 19.5 \). From Figure 2, we find that the error of the SDSS \( u \) is about 0.11 when \( g = 19.5 \). So we set 0.11 as the maximum error. Beneath this value, the SCUSS \( u \) corresponds to the range of \( g < 20.5 \). However, the SDSS \( u \) error is as high as 0.22 when \( g = 20.5 \). In the following, we will convert the SDSS \( u \) to the SCUSS \( u \) for stars brighter than \( g = 20.5 \) so that the error of the converted \( u \) does not exceed 0.11. Here, we only convert the SDSS \( u \) with \( 18.5 < g < 20.5 \) for main-sequence stars. Since \( g-, \, r\)-band magnitudes are much more accurate than those of \( u \), we assume that they are absolutely precise, at least in the considered \( g \)-band magnitude range. So the error of \( u - g \) is the direct consequence of the error of \( u \).

### 3. METHOD

For each object surveyed by the SCUSS, we can identify the same object from the SDSS catalog by matching their positions. So in the merged catalog, each star has the following information: position (R.A. and decl.), \( u \)-band magnitude and its error, SDSS \( u, \, g, \, r, \, i, \, z \)-band magnitudes and their error and extinction. Here, the extinction for the SDSS \( u \)-band magnitude is also used by the SCUSS \( u \)-band magnitude. Throughout this paper, magnitudes and colors are understood to have been corrected for extinction and reddening following Schlegel et al. (1998). We select the stars from the SCUSS catalog using the following criteria:

1. \( 18.5 < g < 20.5 \);
2. \( 0.2 < g - r < 0.8 \);
3. \( 0.6 < (u - g)_{SDSS} < 2.2 \);
4. \( 0.6 < (u - g)_{SCUSS} < 2.2 \);
5. main-sequence stars are selected by only including those objects at distances smaller than 0.15 mag from the stellar locus described by the following equation (Jurić et al. 2008):

\[
(g - r) = 1.39\{1 - \exp[-4.9(r - i)^3 - 2.45(r - i)^2 - 1.68(r - i) - 0.05]\}
\]

6. we further refine the selection of main-sequence stars by only including those objects at distances smaller than 0.3 mag from the stellar locus described by the following equation.

### Table 1: Brief Summary of the SCUSS

| Telescope                  | 2.3 m Bok telescope |
|---------------------------|---------------------|
| Site                      | Kitt Peak in Arizona|
| CCD                       | 2 × 2 4k × 4k CCD array |
| Exposure time             | 300 s               |
| Filter Wavelength         | 3538 Å              |
| Filter FWHM               | 520 Å               |
| Magnitude Limit           | 23.2 mag            |
| Survey Area               | ~5000 deg\(^2\)     |
| Observation Period        | 2010 – 2013         |

![Figure 1](image1.png)

**Figure 1.** Response curves of both the SCUSS \( u \) and the SDSS \( u \) filters. Atmospheric extinction at the airmass of 1.3 is taken into account, and both curves are normalized to their maxima.

![Figure 2](image2.png)

**Figure 2.** Average \( u \) (SDSS and SCUSS) error as a function of \( g \)-band magnitude. Main-sequence stars with \( 0.2 < g - r < 0.8 \) are selected. It is obvious that the error of the SDSS \( u \) is much larger than that of the SCUSS \( u \), especially at the faint end.
equation (Jia et al. 2014):

\[
(u - g)_{\text{SDSS}} = \exp[-(g - r)^2 + 2.8(g - r) - 1]
\]

We divide the color range of \(0.2 < g - r < 0.8\) into six equal bins, and also divide the magnitude range of \(18.5 < g < 20.5\) into 20 bins. Thus, we totally get 120 \(0.1 \times 0.1 \text{ mag}^2\) bins, and designate each square bin by an index computed in the following manner:

\[
\text{index} = \text{int}((u - g - 0.2)/0.1) \times 20 + \text{int}((g - 18.5)/0.1)
\]

where the symbol int stands for the integer portion. In this way the index takes values from 0 to 119. Main-sequence stars whose colors and magnitudes match a position specified by index will be used to construct a “convertor.” Thus, we will obtain a total of 120 convertors, and each convertor is denoted

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**Figure 3.** Two-color diagrams for \((u - g)_{\text{SCUSS}}\) vs. \((u - g)_{\text{SDSS}}\). Main-sequence stars in different magnitude and color ranges are selected. Stars in panels from top row to bottom row are with \(18.5 < g < 18.6, 19.4 < g < 19.5\) and \(20.4 < g < 20.5\) respectively. Stars in panels from left column to right column are with \(0.2 < g - r < 0.3, 0.5 < g - r < 0.6\) and \(0.7 < g - r < 0.8\) respectively. The numbers shown in each panel are the ratios of standard deviation between \((u - g)_{\text{SCUSS}}\) and \((u - g)_{\text{SDSS}}\). These numbers are greater than one, which implies that the SCUSS \(u\) is more accurate than the SDSS \(u\). Additionally, these numbers become larger as the \(g\)-band magnitude becomes fainter, and the largest one corresponds to the bottom left panel (blue and faint).
The slope is almost equal to 1. The data are fitted with a linear line, with the expression shown in the figure. The slope holds. We can evaluate which color is associated with one convertor array. The more scattered the symbol int also stands for the integer portion. Each convertor is further classified with two labels of integer number, and . Each convertor has the form of a matrix in which each element is further denoted as , where , range from 0 to 15. Each main-sequence star that is associated with one convertor index is further denoted as max[index][]. Here, because convertor[index][][][i] can be equal to zero for some values, we can discard them and record the non-zero elements and their positions in a new array. Through this method, the sampling efficiency can be greatly improved.

4. TESTING

From the top three two-color diagrams of Figure 3, we find that may be expressed as a linear function of . For selected stars with , the error of plays a minor role for the distribution of points in these diagrams. If the -band (both SDSS and SCUSS) magnitudes were absolutely precise, the resulting transformation relation would be as follows:

\[(u-g)_{SDSS} = k \times (u-g)_{SCUSS} + h,\]

where is the slope and represents a constant.

In evaluating which color (either or ) has the greater error, the reliability of the standard deviation ratio shown in Figure 3 depends on the assumption \(k \approx 1\). In Figure 4, we plot a two-color diagram of versus for main-sequence stars with . We notice that the error of the -band magnitude at the bright magnitude is small, and therefore its effect on the color distribution in Figure 4 can be neglected. The trend of versus is fitted by a line with the expression shown in the figure. The slope is almost equal to 1. The assumption of holds. We can evaluate which holds. We can evaluate which
greater error by the dispersion degree of the points in Figure 3. In addition, for convenience we may also approximately assume that the SDSS $u$ and SCUSS $u$ are from the same photometric system, since they are almost similar after neglecting the error, as shown in Figure 4.

In order to evaluate the effect of this conversion, we plot histograms of the distribution of $(u - g)_{SDSS}$, $(u - g)_{SCUSS}$ and $(u - g)_{CONV}$ for main-sequence stars with different magnitude and color ranges in Figure 5. The top three panels show color distributions of stars with $18.5 < g < 19$, the middle three with $19.3 < g < 19.7$ and the bottom three with $20 < g < 20.5$. Stars for panels from left column to right column have $0.2 < g - r < 0.3$, $0.5 < g - r < 0.6$ and $0.7 < g - r < 0.8$, respectively. The histograms in each panel are normalized to the maximum, with actual peak values labeled. The histograms of $(u - g)_{CONV}$ and histograms of $(u - g)_{SCUSS}$ nearly coincide, directly reflecting the effectiveness of the conversion from the SDSS $u$ to SCUSS $u$.

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**Figure 5.** Histograms of the distribution of $(u - g)_{SDSS}$ (blue), $(u - g)_{SCUSS}$ (green) and $(u - g)_{CONV}$ (red) with different magnitude and color ranges. Stars for panels from top row to bottom row have $18.5 < g < 19$, $19.3 < g < 19.7$ and $20 < g < 20.5$. Stars for panels from left column to right column have $0.2 < g - r < 0.3$, $0.5 < g - r < 0.6$ and $0.7 < g - r < 0.8$, respectively. The histograms in each panel are normalized to the maximum, with actual peak values labeled. The histograms of $(u - g)_{CONV}$ and histograms of $(u - g)_{SCUSS}$ nearly coincide, directly reflecting the effectiveness of the conversion from the SDSS $u$ to SCUSS $u$. 

In order to evaluate the effect of this conversion, we plot histograms of the distribution of $(u - g)_{SDSS}$, $(u - g)_{SCUSS}$ and $(u - g)_{CONV}$ for main-sequence stars with different magnitude and color ranges in Figure 5. The top three panels show color distributions of stars with $18.5 < g < 19$, the middle three with $19.3 < g < 19.7$, and the bottom three with $20 < g < 20.5$. Corresponding to the color range, stars for panels from left column to right column have $0.2 < g - r < 0.3$, $0.5 < g - r < 0.6$ and $0.7 < g - r < 0.8$, respectively. The histograms in each panel are normalized to the maximum, with the actual peak values labeled. It is clear that the profiles of the histograms of $(u - g)_{CONV}$ in each panel are almost the same as those of $(u - g)_{SCUSS}$. This effect indicates that the conversion has the ability to reduce the error of $u_{SDSS}$, to be as small as that of $u_{SCUSS}$. Actually, the distribution of $(u - g)_{CONV}$ will completely coincide with that of $(u - g)_{SCUSS}$ as long as the number of stars selected is large enough for the histogram, since the convertor arrays are constructed using the SCUSS $u$ data. Thus, for a larger sky area in which there is no SCUSS $u$, the convertor array could be used to reduce the error of SDSS $u$. As a result, the error of the converted $u$ magnitude when $g = 20.5$ is equal to the original error of SDSS $u$ when $g = 19.5$. However, we are still aware that the extent to which this conversion method can reduce the $u$ magnitude error cannot be fully tested until a deeper survey is available.

**5. DISCUSSION**

As is known, $u$-band measurements are very important in deriving the photometric metallicity and therefore for constructing a precise MDF. Because of the relatively shallow survey limit ($u \sim 22$) and the relatively large error in the SDSS $u$-band near the faint end, the application of the photometric metallicity estimates is greatly restricted in the range of $g < 19.5$, an insufficient depth to explore the distant halo and substructures. However, the SCUSS $u$ is 1.5 mag deeper than the SDSS $u$, and its error is smaller than the latter’s error on the
whole. The potential application of the conversion from the SDSS \textit{u} to the SCUSS \textit{u} is very important in deriving relatively accurate photometric metallicities of distant stars. In Paper I, we developed a new method to estimate the photometric metallicity distribution of large numbers of stars. Compared with other photometric calibration methods, this effectively reduces the error induced by the method itself, and therefore enables a more reliable determination of the photometric MDF. However, there is another error source: that of the SDSS \textit{u}-band magnitude. This error behavior limits the application of the method in the range of \( g < 19.5 \) in Paper I, which is same as that of Ivezić et al.’s (2008) photometric metallicity estimator. The more accurate SCUSS \textit{u}-band measurements guarantee the accuracy of the stellar distribution in the \( u - g \) versus \( g - r \) panel, and it extends the application of the method in Paper I to even fainter stars. Thus, the photometric MDF of distant stars such as halo stars or some stream stars can be estimated.

However, only the stars in south Galactic Cap are surveyed by the SCUSS, and these have a more accurate \textit{u} band magnitude; how can we derive the photometric metallicity of stars in the north Galactic hemisphere? The conversion from the SDSS \textit{u} to SCUSS \textit{u} statistically reduces the error of the \textit{u}-band magnitude, which make it possible to estimate the photometric MDF of stars in the whole sky. In this study, we have made the conversion for stars in the range \( 18.5 < g < 20.5 \). This conversion combined with the method introduced in Paper I enables us to estimate the photometric metallicity distribution function for stars at least in the range of \( g < 20.5 \), which is 1 mag deeper than that of spectroscopically surveyed stars. So we can study the chemical structure of the Galactic halo in more detail. Besides the application described above, the more accurate \textit{u} band magnitude from the conversion can be applied to address other scientific issues.

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