Photometry Transformation from $RGB$ Bayer Filter System to Johnson-Cousins $BVR$ Filter System

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Abstract

The $RGB$ Bayer filter system consists of mosaic $R$, $G$, and $B$ filters on the grid of photo sensors which typical commercial DSLR (Digital Single Lens Reflex) cameras and CCD cameras are equipped with. Many unique astronomical data obtained using a $RGB$ Bayer filter system are available, including transient objects, e.g., supernovae, variable stars, and solar system bodies. The utilization of such data in scientific research strongly requires reliable photometry transformation methods. In this work, we develop a series of equations to convert the observed magnitudes in the $RGB$ Bayer filter system ($R_B$, $G_B$, and $B_B$) into the Johnson-Cousins $BVR$ filter system ($B_J$, $V_J$, and $R_C$). The new transformation equations derive the calculated magnitudes in Johnson-Cousins filters ($B_{Jcal}$, $V_{Jcal}$, and $R_{Ccal}$) as functions of magnitudes and colors. The mean differences between the transformed magnitudes and original magnitudes, i.e., the residuals, are $\Delta(B_J - B_{Jcal}) = 0.104$
mag, $\Delta(V_I - V_{I_{cal}}) = 0.054$ mag, and $\Delta(R_C - R_{C_{cal}}) = 0.033$ mag. The calculated Johnson-Cousins magnitudes from the transformation equations show a good linear correlation with the observed Johnson-Cousins magnitudes.

**Keywords:** Data Analysis; Photometry Transformation; Johnson-Cousins Filter System; Bayer Filter System; Open Cluster

### 1. Introduction

Photometric system plays an important role in the quantitative photometric and spectroscopic study of stars and stellar systems. Johnson-Cousins $UBVRI$ photometry system is the most popularly used broad-band photometric systems, and most of the existing optical data have been observed with this system (see Bessell, 2005).

Recently, the opportunity of amateur astronomers taking parts in the scientific research is increasing especially in fields of studying transient objects and variable stars. A large amount of photometry data for either supernovae and/or variable stars are available with amateur CCD cameras, in which $RGB$ Bayer filter system is commonly adopted. Since most of the previously compiled photometry data in astronomical society have been taken with Johnson-Cousins $UBVRI$ photometry system (Rodgers et al., 2006; Stencel, 2013), reliable transformation equations are necessary in order to utilize the data from the $RGB$ filter system.

There have been many works on the transformation of $RGB$ photometry to Johnson-Cousins photometry in the literature (Hoot, 2007; Kloppenborg et al., 2012; Loughney, 2010; Vítek and Blažek, 2012). Especially, it was shown that the filter response function of Bayer Green filter is comparable to that of Johnson $V$ filter (see Kloppenborg et al., 2012; Loughney, 2010). Vítek and Blažek (2012) transformed Bayer filter system to Johnson-Cousins filter system using color index of stars. However, there is no equation that can be used in the conversion of $RGB$ photometry to Johnson $UBVRI$ photometry that reflects spectral types and metallicity of different astronomical sources.

A well-known example of the transformation between the different filter systems is the photometry transformation from Sloan Digital Sky Survey ($SDSS$) filter system to Johnson-Cousins filter system. $SDSS$ provides homogenous $ugriz$ photometry for objects in a large fraction of the northern sky (Rodgers et al., 2006; Chonis and Gaskell, 2008). Smith et al. (2002) and Fukugita et al. (1996) derived a $m(g)$ estimation for Sloan photometry
of the standard stars from Landolt (1992). Bilir et al. (2005) obtained a more accurate \(m(g)\) transformation which covers both \((g - r)\) and \((r - i)\) for late-type dwarf stars. They mainly used color-color correlation to derive equations. Transformation equations are generally dependent on metallicities and luminosity classes (Bilir et al., 2005; Rodgers et al., 2006; Karaali and Yaz Gökçe, 2013). Recently, Ak et al. (2014) derived transformation equations covering a large range of metallicities, e.g. \(-4 \leq [Fe/H] \leq 0.5\) dex for giant stars. Photometry with DSLR RGB filter system may also be transformed, based on the same principle used in SDSS to Johnson-Cousins magnitude conversion.

In this paper, we present our observation of open clusters IC4665 and M52, and derive transformation equations between RGB filter system and Johnson-Cousins \(BVR\) filter system. Basic settings of the observation and preprocessing are described in § 2. § 3 shows process of Point Spread Function (PSF) photometry to derive final transformation equations for M52. § 4 shows results from transformation equations with residuals, and confirm the correlations between the observed data and transformed data using color-magnitude diagrams. This sections also shows the application of the derived transformation equations to IC4665.

2. Observations and data reduction

2.1. Observations of M52

M52 is 60 ± 10 Myr old open star cluster that has a spectral type of B2-G2 (Bonatto and Bica, 2006). \(BVR\) data of M52 were taken on 2014 June 27 (UT) using a 4k × 4k CCD camera with 15 \(\mu\)m pixels and the \(D = 1000\) mm f/7.5 RC-telescope at the Lemmonsan Optical Astronomy Observatory (LOAO), USA. We observed in photometric night with the seeing disk size of \(\sim 3\) pixels \((\sim 2.5''\)) for M52. Images were taken with 18 × 15 sec exposures in \(B\) band, 18 × 9 sec exposures in \(V\) band, and 18 × 8.5 sec exposures in \(R\) band. This data were calibrated by using WEBDA\(^1\) database (Pesch, 1960; Haug, 1970; Wramdemark, 1976; Viskum et al., 1997; Choi et al., 1999; Stetson, 2000; Pandey et al., 2001; Maciejewski and Niedzielski, 2007). CCD temperature was -110°C.

\(^1\)http://www.univie.ac.at/webda/navigation.html
RGB data were taken on 2014 September 10 (UT) with an IR-cut-filter-removed EOS 550D (Canon Inc.) and the D = 300 mm f/8 RC-telescope at Hwasangdae Observatory (HSDO), Hongcheon-gun, Gangwon-do, Korea. The telescope is equipped with a field flattener, which extends the focal length slightly. The effective focal length of the telescope is 2600 mm. The EOS 550D we used have an APS-C (22.3 × 14.9 mm) sized CMOS with 4.3 µm pixels. We select a non-process mode (RAW images) and a low amplification mode (ISO = 400). The full-well capacity for the EOS 550D’s CMOS sensor is about 15300 e−, while the linearity is guaranteed up to 13000 e− at ISO = 400 (Figure 1). Since the background noise increases dramatically as battery charge decreases or after changing batteries (Henden et al., 2014), we used an AC adapter instead of batteries. The field of view for the RGB data of M52 is 28′ × 28′. The RGB data was obtained by 21 × 120 sec exposures with seeing of 4.7 pixels (∼1.6″). Note that the Full Width at Half Maximum (FWHM) of the DSLR images should be larger than 2 pixels to cover all three (Red, Green, and Blue) photosensors.

2.2. Observations of IC4665

IC4665 is 27 Myr old open star cluster that is classified into spectral type of F5 - K5 (Smith et al., 2011; Lodieu et al., 2011). BVR magnitudes of stars in IC4665 are obtained from the WEBDA database (Johnson, 1954; Hogg and Kron, 1955; Alcaino, 1965; McCarthy and O’Sullivan, 1969; Eggen, 1971; Sanders and van Altena, 1972; Muzzio, 1973; Neckel, 1974; Landolt, 1983a; Landolt, 1983b; Menzies et al., 1991; Prosser, 1993; Menzies and Marang, 1996; de Wit et al., 2006).

RGB data of IC4665 were obtained on 2014 April 14 (UT). The observation was made with the EOS 550D attached to a William Optics ZenithStar 80 ED APO telescope (D = 80mm, f/6.8, William Optics Corporation) at the Kyung Hee Astronomical Observatory (KHAO), Gyeonggi-do, Korea. Camera settings are identical to those of M52 observation. The field of view (FOV) of the system is 94′ × 141′. We took 30 frames with 15 sec exposures in photometric night with the seeing disk size of ∼5 pixels (∼8.1″).

Details of the observations, including filters, target coordinates, field of views, and observing conditions are summarized in Table 1.
2.3. Data reduction

Since the RGB Bayer Filter system consists of mosaic RGB filter sets that cover $2 \times 2$ pixels with Red, Green, Green, and Blue colors for each pixel, we need to separate single image into images with different filters. We wrote a python-based program to extract pixels that corresponds to each color to produce R, G, and B filter images. Especially for Green filters, we combined two green filter images by averaging for each set of RGGB filters. Image combining and basic preprocessing were performed with Image Reduction and Analysis Facility (IRAF)$^4$. Even though the CMOS of the DSLR camera was not cooled, the average dark current for sufficiently short exposures (15 seconds) was extremely low to be only $1 \text{ - } 3 \text{ e}^-$. Therefore we did not apply dark subtraction to the object images. We performed bias and flat corrections, then we combined 30 images for each filter to make single object image to reduce random noise.

3. Results

3.1. Photometric data

After producing the combined images for each filter, we derived magnitudes of each stars in star cluster with IRAF/DAOPHOT package. Either moffat15 function or penny2 function was chosen as PSF. We detected 564 stars at $4\sigma$ over sky background in M52 RGB image. After identifying the same stars in BVR images, we compared $\text{mag(Blue)}$ with $\text{mag(B)}$, $\text{mag(Green)}$ with $\text{mag(V)}$, and $\text{mag(Red)}$ with $\text{mag(R)}$ for individual stars to derive conversion formula that describes the correlation between two filter systems. The aperture size for magnitude measurement was 9.4 pixels ($\sim 3.2''$) for the RGB data and 6 pixels ($\sim 5''$) for the BVR data in radius. Stars in M52 have magnitudes and colors in the range of $11.8 \leq V \leq 17.6$ mag and $-0.2 \leq (B - V) \leq 1.07$ mag.

3.2. Transformation equations

We assumed that Johnson $B$, $V$, and $R$ magnitudes can be determined based on the corresponding Bayer magnitudes and colors. The transforma-

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$^4$IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
tion equations are described as follows:

\[ B_J = B_{B,ZP} + B_B + C_{B,BG}(B_B - G_B) + C_{B,GR}(G_B - R_B) \]  \hspace{1cm} (1)

\[ V_J = G_{B,ZP} + G_B + C_{V,BG}(B_B - G_B) + C_{V,GR}(G_B - R_B) \]  \hspace{1cm} (2)

\[ R_C = R_{B,ZP} + R_B + C_{R,BG}(B_B - G_B) + C_{R,GR}(G_B - R_B) \]  \hspace{1cm} (3)

In these equations, \( B_J \), \( V_J \), and \( R_C \) mean Johnson \( B \), \( V \), and Cousins \( R \) magnitudes, respectively. Also, \( B_B \), \( G_B \), and \( R_B \) indicate Bayer \( B \), \( G \), and \( R \) magnitudes, respectively. In addition, we include \( B_{B,ZP} \), \( G_{B,ZP} \), and \( R_{B,ZP} \) representing zero-points at Bayer filters. Zero-points vary depending on the observing conditions such as weather, airmass, etc. Coefficients were derived by iterating the least square fitting algorithm with sigma clipping method (see Table 2).

Figure 2 shows the distribution of magnitude residuals, i.e., the difference between the observed magnitudes and the calculated magnitudes based on the transformation equations. Most of the objects fall near the zero residual line, which shows that the reliability of transformation equations. However, there also exist a number of outliers especially in \( B \) filter.

4. Discussion

4.1. Accuracy of the RGB transformation

We derived Root Mean Square (\( RMS \)) values to test the accuracy of transformation equations. \( RMS \) errors for M52 are 0.138, 0.071, and 0.043 for \( B_J \), \( V_J \) and \( R_C \), respectively (Table 2).

As Figure 2 has shown that the dispersion around the zero line is the smallest in the case of \( R \) and the largest in the case of \( B \). The \( RMS \) values also suggest that the conversion into \( R_C \) magnitudes are more reliable than that of \( B_J \) magnitudes.

The differences between magnitude residuals for different filters are noticeable in color-color diagrams as well (Figure 3). The scatters are larger in the top panel than in the bottom panel. The large \( RMS \) errors may arise from the contamination of Balmer discontinuity in the \( B_B \) band.

In Figure 4, we plot the color-magnitude diagram of M52. Most of the stars in M52 falls into the main sequence. The similarity in color magnitude diagrams constructed using the observed Johnson-Cousins filter system magnitudes and the transformed magnitudes shows that the transformation equations work well.
If we divide stars into two groups (one for main sequence stars and the other for giants), we find that RMS errors for main sequence stars are lower than that of giants. Stars with $V - R < 0.75$ are considered to be spectral type F and G main sequence stars and stars with $V - R \geq 0.75$ are considered to be K giants. Our transformation equations are mostly based on the main sequence stars (see Table 3), since they are more numerous (448 stars) than giant stars (62 stars). Another reason for this difference is that the late-type stars have more absorption lines than the early-type stars in their spectrum.

4.2. Application to IC4665

We applied our transformation equations to RGB magnitudes of IC4665. IC4665 is a younger open cluster which consists of main sequence stars and sub-giants. RGB magnitudes of stars in IC4665 were also derived using IRAF/DAOPHOT with the same method used for M52. 63 stars were detected with 4σ, and their RGB magnitudes were transformed into BVR magnitudes using the transformation equation derived in § 3.2. All coefficients in equations (1) - (3) except the zeropoints are maintained to be the same. Figure 5 shows color magnitude diagrams of IC4665 constructed using the observed magnitudes from WEBDA (top), and the transformed Johnson-Cousin magnitudes from RGB magnitudes (bottom).

The color-magnitude diagram using the transformed magnitudes follows the same trends as the observed diagram. This resemblance represents the coefficients works well not only for M52 but also for other clusters. As we discussed in § 4.1, the diagram shows that the scatter in magnitude conversion is larger in the case of B filter compared to that of other filters. This deviations are particularly prominent in the sub-giant region.

5. Summary

Equations (1), (2), and (3) convert RGB Bayer filter system to Johnson-Cousins filter system. The color terms, $B_B - G_B$ and $G_B - R_B$ are included in the transformation equations. The obtained coefficients are listed in Table 2.

There have been a number of previous attempts for filter transformation (e.g., Rodgers et al., 2006; Chonis and Gaskell, 2008; Smith et al., 2002; Karaali and Yaz Gökçe, 2013; Ak et al., 2014). The best instrumental fits before our research was obtained by Hoot (2007), who have presented RMS
errors of 0.347, 0.134 and 0.236 magnitude for $B$, $V$, and $R$ bands, respectively. Our results are more reliable than those of Hoot (2007), because of two color terms in the transformation equations.

The limitation of the transformation equations derived in this study is that they were derived only from a single star cluster which contain relatively young stars. Although the equations can be applied to other open cluster data (IC4665), the scatter for magnitude conversion increases in the sub-giant regions. Further works are needed in order to construct the magnitude transformation equations for stars with different spectral types and metallicities. Our final goal is to find the coefficient of transformation equations which can be applied to stars of various spectral types and metallicities.

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Table 1: Observation log

| Date       | Observatory and Telescope | Filters$^e$ | Target | R.A.       | Dec.(J2000)       | FoV$^a$ | Seeing (") |
|------------|---------------------------|-------------|--------|------------|------------------|--------|------------|
| 2014 Apr 14 | KHAO$^b$, 0.08m telescope | $RGB$       | IC4665 | 17h46m18s  | +05°46'00"       | 94' × 141' | 8.1        |
| 2014 Jun 28 | LOAO$^c$, 1m telescope   | $BVR$       | M52    | 11h24m48s  | +61°35'36"       | 28' × 28' | 2.5        |
| 2014 Oct 09 | HSDO$^d$, 0.3m telescope | $RGB$       | M52    | 11h24m48s  | +61°35'36"       | 23' × 30' | 1.6        |

$^a$ Field of View
$^b$ Kyung Hee Astronomical Observatory, http://khao.khu.ac.kr
$^c$ Lemmonsan Optical Astronomy Observatory, http://loao.kasi.re.kr
$^d$ Hwasangdae Observatory, 915-2 Hwasangdae-ri, Naechon-myeon, Hongcheon-gun, Gangwon-do, Korea
$^e$ $RGB$ is Bayer $RGB$ filter system for Canon EOS 550D, and $BVR$ is Johnson-Cousins filter system.
Table 2: Coefficients and RMS variation by Sigma Clipping method

|       | Original Data | 1st SC<sup>a</sup> | 2nd SC<sup>a</sup> |
|-------|---------------|---------------------|--------------------|
| \( B_{B,ZP} \) | -0.497 | -0.384 | -0.339 |
| \( C_{B,BG} \) | 1.088 | 0.259 | 0.421 |
| \( C_{B,GB} \) | 1.883 | 2.349 | 1.920 |
| RMS   | 0.38 | 0.18 | 0.14 |
| \( G_{B,ZP} \) | -0.635 | -0.551 | -0.529 |
| \( C_{V,BG} \) | 1.060 | 0.519 | 0.649 |
| \( C_{V,GR} \) | 0.421 | 0.706 | 0.439 |
| RMS   | 0.28 | 0.1  | 0.07 |
| \( R_{B,ZP} \) | -0.673 | -0.617 | -0.617 |
| \( C_{R,BG} \) | 0.325 | 0.015 | 0.088 |
| \( C_{R,GR} \) | 0.324 | 0.481 | 0.387 |
| RMS   | 0.23 | 0.06 | 0.04 |

<sup>a</sup> Sigma Clipping method with 2.5\( \sigma \)
Table 3: *RMS* values for transformation equations in main sequence and giants

|       | Main sequence | Giants |
|-------|--------------|--------|
| $B_J$ | 0.107        | 0.208  |
| $V_J$ | 0.060        | 0.107  |
| $R_C$ | 0.042        | 0.051  |
Figure 1: Linearity plot for EOS 550D. The dashed line represents linearity while well fitted up to 13000 $e^-$. The full-well capacity is 15300 $e^-$. Data are obtained by taking flat images.
Figure 2: Magnitude residual plots for M52. Y-axis represents the difference between the calculated Johnson-Cousins magnitudes and the observed Johnson-Cousins magnitudes. From top to bottom, $B_J$, $V_J$, and $R_C$ band data points are plotted. The horizontal dotted line represents zero residual.
Figure 3: Comparison between $RGB$ color vs. $BVR$ color for stars in M52. Upper diagram shows larger scattering because of the larger errors in $B_B$ band. Dotted lines represent 2$^{nd}$ order fitting lines.
Figure 4: M52 color-magnitude diagrams from observed data (top) and calculated data (bottom). The yellow dashed line represents main sequence and the red dotted line represents giants. The color-magnitude diagram based on the magnitudes from transformation equation (bottom) is consistent with that of the observed Johnson V and Cousins R magnitude (top).
Figure 5: IC4665 color-magnitude diagrams from observed data (top) and calculated data (bottom). Calculated data are derived using coefficients of M52. Only zero-points are newly set for IC4665. For main-sequence stars, the color-magnitude diagram based on calculated data (bottom) are consistent with that of the observed Johnson $B$ and Cousins $V$ magnitude (top). On the other hand, sub-giants have different magnitudes between calculated data (bottom) and observed data (top) for a Johnson $B$ filter system.