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Transformation Equations Between *GALEX* and *UBV* Photometric Systems

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Abstract: The insufficiency of photometric data in the *U*-band of the FGK-type stars in the solar neighborhood makes difficult to determine the flux of the blue region of their spectral energy distributions, and causes to the inadequacy in the estimation of the photometric metallicity and the color excesses of these stars. To overcome this problem, the *U-V* color indices of 556 stars in different luminosity class, whose spectroscopic, photometric and astrometric data are well known, were calculated using derived transformation equations sensitive to *GALEX* and *BV* color indices. In order to obtain the transformation equations, *GALEX* DR7 *FUV*, *NUV* and Johnson-Morgan *UBV* photometric data were used. Model atmosphere parameters (T_{eff}, log *g*, [Fe/H]) collected from the literature concerning the stars were separated into different metal abundance intervals and HR diagrams were created. Then PARSEC mass tracks were added to these HR diagrams to determine the luminosity classes of the stars in the sample. The transformation equations, which were designed based on two color indices, were derived for stars in different luminosity classes. The analyses showed that *U-V* color index calculations performed by the newly obtained photometric transformation equations, provide highly sensitive results ($\Delta(U\text{-}V)_0 \sim 0.05$ mag).

Keywords: star: main-sequence, technical: photometric – catalogue – sky survey. Inadequacy of photometric data in the U-filter of FGK type stars in the solar neighborhood

INTRODUCTION

Today, photometric sky survey observations are systematically performed to cover the ultraviolet (UV) and infrared regions of the electromagnetic spectrum. In spectroscopic sky surveys, spectroscopic observations of a limited number of objects classified according to their position in color spaces are made as a result of photometric observations. Since the luminosity of these objects is different from each other, the main-sequence stars provide information about the solar neighborhood, while the evolved stars provide information about the old thin disc, thick disc and halo populations of our Galaxy beyond the solar vicinity. However, the number of stars observed as a result of systematically ongoing spectroscopic sky survey programs and spectral analyses of these stars do not exceed one million in total. For this reason, precise measurements of photometric sky surveys, which contain more than a billion of bright and faint objects, still important in testing models about the structure and evolution of the Galaxy.

UBV which has been used as a standard photometric system since the second half of the 20th century, has been used frequently in observations of bright single stars or multiple stellar systems. When the apparent magnitudes of the stars is fainter (V > 10 mag), the decrease in measurement accuracy of the short wavelengths leads to a major deficiency in the U-band observations of the stars. On the other hand, the *UBV* photometric system was not used in any systematic sky survey programs. The low transmissivity of the Earth's atmosphere in the *U*-band has led to the need for observation outside the atmosphere. Moreover, thanks to the latest advances in satellite technology, the Galaxy Evolution Explorer (*GALEX*) satellite has been designed and the UV observations of objects have become feasible from outside the Earth's atmosphere [1].

The *GALEX* satellite was launched into space in 2003 and continued its active mission until 2012. It is the first satellite to observe the entire sky with two detectors, i.e. far ultraviolet (*FUV*, λ_{eff} = 1528 Å; 1344 – 1786 Å) and near ultraviolet (*NUV*, λ_{eff} = 2310 Å; 1771 – 2831 Å). Measurements in the far and near UV bands of approximately 583 million objects obtained from reduction of 100865 images from satellite observations are given in DR7 version in *GALEX* database [2]. In this work, transformation equations between the color indices of stars in different luminosity classes observed in *GALEX* and *UBV* photometric systems were obtained. This has enabled the empirical calculation

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of the *U-V* color index of the stars. By means of these transformation equations, the UV excesses of the FGK spectral type main-sequence stars without *U* observations can be calculated and photometric metal abundances can be obtained. In addition, these equations have an important role in eliminating *U*-band deficiency for spectrophotometric studies of stars.

DATA

In order to obtain transformation equations between *GALEX* and *UBV* photometric systems, we prioritized the stars that have sensitive spectroscopic, astrometric and photometric data in the literature. In this context, we used the spectroscopic data from 14 works [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. We selected 6149 stars whose atmospheric model parameters (T_{eff}, log *g* and [Fe/H]) were derived in these works. In order to derive transformation equations, we searched both *GALEX* DR7 [2] and *UBV* [17, 18, 19, 20, 21, 22] photometric data as well as *Gaia* DR2 [23] trigonometric parallax data from catalogues in the literature. This reduced the number to 556 stars which spectroscopic, photometric and astrometric data was available. PARSEC mass tracks in different metal abundances were used to determine the luminosity classes of the stars in the sample [24]. The stars between the ZAMS and TAMS curves are classified as main-sequence, stars above the TAMS curve with $\log g \geq 3.5$ as sub-giant, and stars with $\log g < 3.5$ as giant. Based on these criteria, 245 of 556 stars in our sample are main-sequence, 187 are sub-giant and 124 are giant.

Since we use photometric data in this work, the absorption and reddening effects caused by the interstellar medium should be considered. We used the dust map of [25] in order to remove the absorption and reddening effects of the interstellar medium. Since the absorption in a star's direction obtained from the dust map is given for the Galactic border, this absorption value should be reduced to the distance between the Sun and the relevant star. We adopted the total absorption $A_\infty(b)$ in *V*-band for a star's direction obtained from the dust map of [25] and estimated absorption $A_d(b)$ for the distance between Sun and the star using the following equation of [26];

$$A_d(b) = A_\infty(b)\left(1 - e^{\frac{-|d\sin(b)|}{H}}\right) \quad (1)$$

here, *d* and *b* denote the distance of the star and Galactic latitude, respectively. *H* is the scaleheight of the Galactic dust (H = 125 pc; [27]). We calculated the distances of the stars from *Gaia* DR2 trigonometric parallaxes using the equation of d (pc) = $1000/\pi$ (mas). The median distances of the main-sequence, sub-giant and giant stars in the sample are 33, 49 and 83 pc, respectively. The color excess of the star ($E_d(B\text{-}V)$) in question could be calculated from equation (2) [28] and the color excess $E_d(U\text{-}B)$ was obtained using equation (3) [29]:

$$E_d(B - V) = A_d(b)/3.1 \quad (2)$$

$$E_d(U - B) = 0.72E_d(B - V) + 0.05E_d^2(B - V) \quad (3)$$

The de-reddened apparent magnitudes, (V_0, FUV_0, NUV_0), and color indices ($(U\text{-}B)_0$, $(B\text{-}V)_0$) are then calculated by following equations [28, 29, 30],

$$\begin{aligned} V_0 &= V - 3.1 \times E_d(B - V) \\ (FUV)_0 &= FUV - 4.37E_d(B - V) \\ (NUV)_0 &= NUV - 7.06E_d(B - V) \\ (B - V)_0 &= (B - V) - E_d(B - V) \\ (U - B)_0 &= (U - B) - E_d(U - B) \end{aligned} \quad (4)$$

The fact that the stars in the sample are located in solar neighborhood is consistent with the calculated small color excesses. The positions of the 556 calibration stars on the $(U\text{-}V)_0 \times (B\text{-}V)_0$ (a) and the $(U\text{-}V)_0 \times (FUV\text{-}NUV)_0$ two-color diagrams are shown in Figure 1 in accordance with their luminosity classes.

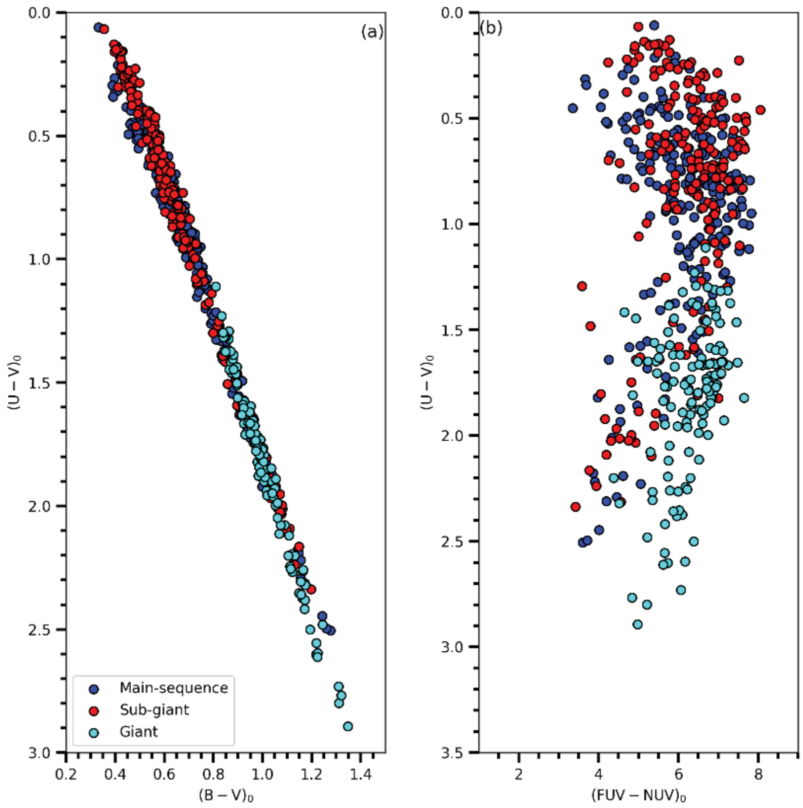

FIGURE 1. The positions of the 556 stars on the $(U\text{-}V)_0 \times (B\text{-}V)_0$ (a) and the $(U\text{-}V)_0 \times (FUV\text{-}NUV)_0$ (b) two-color diagrams according to their luminosity classes.

RESULTS

556 calibration stars with well-known observational parameters were used to obtain the transformation equations. The following equation is preferred for the transformation from the UV bands to optical bands:

$$(U - V)_0 = a(FUV - NUV)_0 + b(B - V)_0 + c \tag{5}$$

The coefficients *a*, *b* and *c* in the equation are calculated by multiple regression method for stars of different luminosity class (main-sequence, sub-giant, and giant) and the results are listed in Table 1. Correlation coefficient and standard deviation for each equation are also given in the last two columns of Table 1. The correlation coefficients are high and the standard deviations are small in the transformation equations. It was found that there were no systematic differences between the calculated $(U\text{-}V)_{\rm cal}$ and observed $(U\text{-}V)_{\rm obs}$ color indices and the residues ($\Delta(U\text{-}V)_0 = (U\text{-}V)_{\rm cal} - (U\text{-}V)_{\rm obs}$) were mostly small. However, the fact that the error of the coefficient *a* calculated for the giant stars is greater than itself indicates that the sensitivity of the color index $(FUV\text{-}NUV)_0$ is low in the transformations performed for the stars of this luminosity class.

TABLE 1. The number of stars (*N*), coefficients (*a*, *b*, *c*), correlation coefficients (R^2) and standard deviation (σ) values of three luminosity classes for the equation (4). Errors of the coefficients are given in brackets.

Luminosity Class	*N*	*a*	*b*	*c*	R^2	σ
Main-sequence	24	-0.042159 (0.003659)	2.65427 (0.02125	-0.63791 (0.02827)	0.98	0.05
Sub-giant	18	-0.020667 (0.004340)	2.79537 (0.02161	-0.88118 (0.03417)	0.99	0.05
Giant	12	0.002630 (0.007415)	3.18474 (0.04374	-1.37664 (0.07691)	0.98	0.05

SUMMARY AND CONCLUSION

In this work, considering the 556 stars with sensitive spectroscopic, photometric and astrometric data in the literature, the transformation equations between *GALEX* and *UBV* data are obtained as a function of luminosity classes. These photometric transformation equations are especially important for *U*-band magnitude unmeasured FGK type main-sequence stars. Since the metallicities of these stars nearly do not change throughout their main-sequence life, it is an effective method to determine metal abundances using photometric color indices [31, 32]. This is important in investigating the formation and chemical evolution of the Milky Way.

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