Photonic Passbands and Zero Points for the Strömgren $uvby$ System

MICHAEL S. BESSELL

Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, The Australian National University, ACT 2611, Australia; bessell@mso.anu.edu.au

Received 2011 September 16; accepted 2011 November 9; published 2011 December 2

ABSTRACT. Photonic passbands have been derived for the $uvby$ standard system by convolving the original filter passbands of Strömgren and Perry with atmospheric extinction and the QE of a cooled 1P21 photomultiplier tube. Using these new passbands, synthetic photometry was calculated for all the stars in the extensive NGSL and MILES spectrophotometric libraries and compared with the homogenized $b - y$, $m_1$, and $c_1$ indices in the Hauck-Mermilliod 1998 catalog and the derived $u - v$ and $v - b$ colors. Excellent agreement between observed and synthetic photometry was achieved with regression slopes near unity. Slightly better fits were obtained by considering stars with $b - y < 0.5$ and $b - y > 0.5$, separately. It is recommended that these new passbands be used together with the provided transformation equations to generate synthetic photometry from model atmosphere fluxes and observed spectrophotometry. Synthetic photometry was also carried out using the natural system of the four-channel spectrograph photometers and those of Cousins and Eggen in order to explore the systematic differences that could be expected between their instrumental systems and the standard system.

Online material: color figures

1. INTRODUCTION

The Strömgren $uvby$ system (Strömgren 1966), is a widely used intermediate-band photometric system comprising data for more than 63,300 stars in the homogenized Hauck & Mermilliod (1998) catalog. It has long been considered a precise and accurate standard system that is very useful for determining temperatures and effective gravities of B, A, F, and early-G stars and metallicities of F and G stars. However, the use of different filters at many observatories and the extension of the photometry to late-G and K stars and to supergiants and reddened stars has resulted in significant systematic differences in the instrumental systems between observers. The recommended method of photometric data reduction to derive the indices $c_1 = (u - v) - (v - b)$ and $m_1 = (v - b) - (b - y)$, rather than the colors $u - v$ and $v - b$ directly, has also resulted in larger uncertainties in the transformed indices, mainly for the cooler stars. These problems have been vividly illustrated and discussed by Manfroid (1984) and Manfroid & Sterken (1987).

A large database of excellent $uvby$ photometry has been obtained with the four four-channel spectrograph photometers (Helt et al. 1987) on telescopes at Kitt Peak, La Silla, and San Pedro Martir (e.g., Olsen 1983, 1993; Schuster & Nissen 1988). Figure 1 in Olsen (1983) shows the complicated decision processes carried out to transform this well-defined and stable natural system photometry onto the standard system. Cousins (1987) also discussed the nonlinearities involved in successfully transforming his E-region photometry onto the standard system, and Eggen (1976) outlined issues associated with a too-narrow $v$ filter. Given these different and complex transformations, one may wonder whether passbands can be defined that accurately represent the homogenized $uvby$ system.

In the last few years, two libraries of accurate higher-resolution ($R \sim 1000–2000$) spectrophotometric data have become available—Next Generation Spectral Library (NGSL; Heap & Lindler 2007) and Medium-Resolution Isaac Newton Telescope Library of Empirical Spectra (MILES; Sanchez-Blazquez et al. 2006), and most of the stars in these spectral libraries also have Hipparcos $H_p$ magnitudes—enabling Bessell & Murphy (2011) to renormalize the spectrophotometry onto a precise absolute scale by synthesizing the $H_p$ magnitudes. Many of these stars are also in the Hauck & Mermilliod (1998) $uvby$ catalog, thus providing the opportunity to critically compare the synthetic $uvby$ photometry with the standard values.

2. THE $uvby$ PASSBANDS

Matsushima (1969) and Crawford & Barnes (1979) published transmissions of the Kitt Peak National Observatory (KPNO) $uvby$ filter set No. 1 that was used when setting up the original $uvby$ system by Strömgren & Perry (1965, unpublished). These filter functions are considered to be the best starting point for synthetic $uvby$ photometry calculations. Synthetic photometry based on model atmosphere fluxes has been computed by many authors (Matsushima 1969; Relyea & Kurucz 1978; Kurucz 1979; Clem et al. 2004; Önehag et al. 2009) and while most have convolved the filter functions with a 1P21 sensitivity function, Al mirror reflectivity, and one air...
mass of extinction, some (e.g., Matsushima 1969; Maiz Appellanz 2006) have used the filter transmissions directly.

The product of the filter passband, the atmospheric transmission, the mirror reflectivity, and the detector sensitivity function is called the system response function or system passband. In the past, the detector sensitivity function that was used related to the energy measured. Nowadays, with photon-counting detectors being the norm, the detector sensitivity function used relates to the number of photons measured. The resultant system response functions or system passbands therefore differ, depending on whether they reflect the energy of the photons or the number of photons. As modern synthetic photometry packages, such as Synphot, assume that system response functions are in the photon form, we will use that form in this article and also use the terms “photonic response function” or “photonic passband” to distinguish them from the alternative energy forms.

The 1P21 sensitivity function is from Kurucz (1979, Table 7); this has the same UV cut-on as measured by Bessell (1979, Table 1.1) and appears to have a similar red cutoff to that measured by Young (1963, Fig. 6). It is presumed to be in terms of the photocathode radiant response (in units of mA W$^{-1}$), and we have converted it into QE to derive the photonic response (see Bessell & Murphy 2011). The mirror reflectivity (see values in Helt et al. 1987) was neglected, but we applied 1.2 air masses of typical Siding Spring Observatory (1200 m) extinction.

In Table 1 we list our adopted normalized system photonic passbands $S_x(\lambda)$ for $u$, $v$, $b$, and $y$, and in Figure 1 we show the passbands compared with those of Maiz Appellaniz (2006) and the four-channel spectrograph photometers (Helt et al. 1987).

### 3. COMPARISON BETWEEN SYNTHETIC PHOTOMETRY AND STANDARD PHOTOMETRIC VALUES

The synthetic photometry was computed by evaluating, for each of the $uvby$ bands, the expression (see Bessell & Murphy 2011)

$$\text{mag}_x = AB - \text{ZP}_x,$$

where

$$AB = -2.5 \log \frac{\int f_x(\nu)S_x(\nu) d\nu / \nu}{\int S_x(\nu) d\nu / \nu} - 48.60$$

and $f_x(\nu)$ is the observed absolute flux in erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$, $f_x(\lambda)$ is the observed absolute flux in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, $S_x(\lambda)$ is the photonic passband (Table 1), $\lambda$ is the wavelength in angstroms, and ZP$x$ is the zero-point magnitude for each band.

For accurate synthetic photometry it is important that the passbands provided to the integration routines are well sampled and smooth. It is therefore necessary to interpolate the coarsely sampled values of the passbands in Table 1 to a finer spacing of a few angstroms using a univariate spline or a parabolic interpolation routine.

| Wave | $u$ | $v$ | $W$ | $b$ | $W$ | $y$ |
|------|----|----|-----|----|-----|----|
| 3150 | 0.000 | 3750 | 0.000 | 4350 | 0.000 | 5150 | 0.000 |
| 3175 | 0.004 | 3775 | 0.003 | 4375 | 0.010 | 5175 | 0.022 |
| 3200 | 0.050 | 3800 | 0.006 | 4400 | 0.023 | 5200 | 0.053 |
| 3225 | 0.122 | 3825 | 0.016 | 4425 | 0.039 | 5225 | 0.082 |
| 3250 | 0.219 | 3850 | 0.029 | 4450 | 0.056 | 5250 | 0.116 |
| 3275 | 0.341 | 3875 | 0.044 | 4475 | 0.086 | 5275 | 0.194 |
| 3300 | 0.479 | 3900 | 0.060 | 4500 | 0.118 | 5300 | 0.274 |
| 3325 | 0.604 | 3925 | 0.096 | 4525 | 0.188 | 5325 | 0.393 |
| 3350 | 0.710 | 3950 | 0.157 | 4550 | 0.287 | 5350 | 0.579 |
| 3375 | 0.809 | 3975 | 0.262 | 4575 | 0.457 | 5375 | 0.782 |
| 3400 | 0.886 | 4000 | 0.404 | 4600 | 0.681 | 5400 | 0.928 |
| 3425 | 0.939 | 4025 | 0.605 | 4625 | 0.896 | 5425 | 0.985 |
| 3450 | 0.976 | 4050 | 0.810 | 4650 | 0.998 | 5450 | 0.999 |
| 3475 | 1.000 | 4075 | 0.958 | 4675 | 1.000 | 5475 | 1.000 |
| 3500 | 0.995 | 4100 | 1.000 | 4700 | 0.942 | 5500 | 0.997 |
| 3525 | 0.981 | 4125 | 0.973 | 4725 | 0.783 | 5525 | 0.938 |
| 3550 | 0.943 | 4150 | 0.882 | 4750 | 0.558 | 5550 | 0.789 |
| 3575 | 0.880 | 4175 | 0.755 | 4775 | 0.342 | 5575 | 0.574 |
| 3600 | 0.782 | 4200 | 0.571 | 4800 | 0.211 | 5600 | 0.388 |
| 3625 | 0.659 | 4225 | 0.366 | 4825 | 0.130 | 5625 | 0.232 |
| 3650 | 0.525 | 4250 | 0.224 | 4850 | 0.072 | 5650 | 0.143 |
| 3675 | 0.370 | 4275 | 0.134 | 4875 | 0.045 | 5675 | 0.090 |
| 3700 | 0.246 | 4300 | 0.079 | 4900 | 0.027 | 5700 | 0.054 |
| 3725 | 0.151 | 4325 | 0.053 | 4925 | 0.021 | 5725 | 0.031 |
| 3750 | 0.071 | 4350 | 0.039 | 4950 | 0.015 | 5750 | 0.016 |
| 3775 | 0.030 | 4375 | 0.027 | 4975 | 0.011 | 5775 | 0.010 |
| 3800 | 0.014 | 4400 | 0.014 | 5000 | 0.007 | 5800 | 0.009 |
| 3825 | 0.000 | 4425 | 0.006 | 5025 | 0.003 | 5825 | 0.004 |
| 3850 | 0.000 | 4450 | 0.000 | 5050 | 0.000 | 5850 | 0.000 |

**Fig. 1.—Photonic passbands in this article compared with those of Maiz Appellaniz (2006), and Helt et al. (1987).** See the electronic edition of the PASP for a color version of this figure.
Fig. 2.—The $b - y$ regressions. Stars with $b - y < 0.5$ and $b - y > 0.5$. NGSL stars (left) and MILES stars (right). The coefficients of the linear fits are given in Table 2. See the electronic edition of the PASP for a color version of this figure.

Fig. 3.—The $m_1$ regressions. See the electronic edition of the PASP for a color version of this figure.
Fig. 4.—The $c_1$ regressions. See the electronic edition of the PASP for a color version of this figure.

Fig. 5.—The $v - b$ regressions. See the electronic edition of the PASP for a color version of this figure.
First, the CALSPEC stis005 spectrum for Vega was used to derive the AB magnitude zero points of $-0.308$, $-0.327$, $-0.187$, and $-0.027$ for $u$, $v$, $b$, and $y$, respectively, adopting for Vega, $y = 0.03$ (Bessell 1983), $(b - y) = 0.004$, $m_1 = 0.157$, and $c_1 = 1.088$ (Hauck & Mermilliod 1998).

We then computed synthetic colors for all the renormalized NGSL (376) and MILES (830) spectra (Bessell & Murphy 2011) and matched the stars against the homogenized Hauck & Mermilliod (1998) catalog, yielding 259 and 535 objects, respectively, with both spectrophotometry and $uvby$ photometry.

The color differences and index differences were regressed against $b - y$, $m_1$, and $c_1$, and little evidence of residuals that were a continuous function of color was found. Any variation with color that was evident was better dealt with by splitting the sample into blue and red stars, rather than fitting an overall color term. Those stars with $b - y > 0.5$ also showed slightly more scatter than did the bluer stars, which could have been anticipated, since the $uvby$ system was initially standardized for the bluer stars and extended later to the redder stars using a greater range of instrumental systems and only a few red standards.

Fig. 6.—The $u - v$ regressions. See the electronic edition of the PASP for a color version of this figure.

Fig. 7.—Synthetic $V - y$ regressions. See the electronic edition of the PASP for a color version of this figure.
The same order as the observational values reported by Crawford from the NGSL spectra, although the scatter is slightly higher. It is recommended that the transformation equations derived from the NGSL stars be used to convert synthetic photometry onto the same system.

The mean wavelength of the $V/C0_b$ band is clearly very close to that of the $V$ band. Figures 2–6 show the regressions for $b - y$, $m_1$, $c_1$, $u - v$, and $v - b$ overlaid with the lines fitted to the blue and red spectra separately. There were about 185 blue and 70 red spectra in the NGSL sample and 360 blue and 150 red spectra in the MILES sample. In many cases the same fitted line for blue and red stars could suffice within the uncertainties, but for some colors and indices, small blue/red star differences were evident.

Figure 7 shows the synthetic $V - y$ regressions against $b - y$; the $V$ passband is from Bessell & Murphy (2011). The mean wavelength of the $y$ band is clearly very close to that of the $V$ band.

Table 2 lists the results of the least-squares linear fits to the regressions, including the uncertainties in the coefficients and the residual rms. It is recommended that the transformation equations determined from the space-based NGSL spectra be used to convert synthetic photometry onto the same system as the Hauck & Mermilliod (1998) catalog; however, the equations from the MILES fits are in excellent agreement with those from the NGSL spectra, although the scatter is slightly higher. It should also be noted that the slopes of the transformations are of the same order as the observational values reported by Crawford & Barnes (1979) using KPNO filter set No 1.

### Table 2

Zero Points and Slopes in Form of $I_{027} = a_0 + a_1 I_{039}$ from Synthetic Photometry

| Index | NGSL\* | MILES |
|-------|--------|-------|
|       | $a_0$  | $a_1$  | RMS  | $a_0$  | $a_1$  | RMS  |
| $b - y$ | $-0.007$ | $0.001$ | $0.997$ | $0.005$ | $0.007$ | $0.002$ | $0.001$ | $0.986$ | $0.004$ | $0.010$ |
| $m_1$ | $0.005$ | $0.002$ | $0.979$ | $0.010$ | $0.006$ | $0.007$ | $0.958$ | $0.005$ | $0.013$ |
| $c_1$ | $0.011$ | $0.005$ | $0.963$ | $0.012$ | $0.022$ | $0.021$ | $0.002$ | $0.988$ | $0.012$ | $0.019$ |
| $v - b$ | $0.016$ | $0.002$ | $0.994$ | $0.004$ | $0.035$ | $-0.025$ | $0.005$ | $1.041$ | $0.008$ | $0.052$ |
| $u - v$ | $-0.003$ | $0.009$ | $1.018$ | $0.021$ | $0.035$ | $-0.023$ | $0.017$ | $1.064$ | $0.040$ | $0.075$ |
| $V - y$ | $0.024$ | $0.009$ | $0.987$ | $0.003$ | $0.200$ | $0.019$ | $0.001$ | $1.001$ | $0.003$ | $0.011$ |

Note.—The synthetic photometry used zero-point values determined from the CALSPEC stis005 Vega spectrum. The AB magnitude zero points were $-0.308$, $-0.327$, $-0.187$, and $-0.027$ for $u$, $v$, $b$, and $y$, respectively.

It is recommended that the transformation equations derived from the NGSL stars be used to convert synthetic $uvby$ photometry onto the same system as the Hauck & Mermilliod (1998) catalog.

First-line entry for each index is for $b - y < 0.5$. The second line is for $b - y > 0.5$.

The $u$ and $c_1$ data for the MILES data are more uncertain because the spectra have been extrapolated 400 Å to the UV.

### Table 3

Normalized (Helt et al. 1987) $uvby$ Photonic Passbands

| Wave  | $u$ | Wave  | $v$ | Wave  | $b$ | Wave  | $y$ |
|-------|-----|-------|-----|-------|-----|-------|-----|
| 3320  | 0.000 | 4000  | 0.000 | 4560  | 0.000 | 5340  | 0.000 |
| 3340  | 0.349 | 4020  | 0.427 | 4580  | 0.304 | 5360  | 0.389 |
| 3360  | 0.492 | 4040  | 0.754 | 4600  | 0.576 | 5380  | 0.672 |
| 3380  | 0.581 | 4060  | 0.884 | 4620  | 0.906 | 5400  | 0.912 |
| 3400  | 0.687 | 4080  | 0.979 | 4640  | 0.994 | 5420  | 1.000 |
| 3420  | 0.789 | 4100  | 0.995 | 4660  | 1.000 | 5440  | 0.982 |
| 3440  | 0.835 | 4120  | 1.000 | 4680  | 0.969 | 5460  | 0.953 |
| 3460  | 0.879 | 4140  | 0.996 | 4700  | 0.921 | 5480  | 0.913 |
| 3480  | 0.926 | 4160  | 0.942 | 4720  | 0.871 | 5500  | 0.850 |
| 3500  | 0.960 | 4180  | 0.742 | 4740  | 0.864 | 5520  | 0.798 |
| 3520  | 0.982 | 4200  | 0.440 | 4760  | 0.804 | 5540  | 0.759 |
| 3540  | 0.992 | 4220  | 0.219 | 4780  | 0.522 | 5560  | 0.725 |
| 3560  | 1.000 | 4240  | 0.000 | 4800  | 0.186 | 5580  | 0.631 |
| 3580  | 1.000 | 4260  | 0.000 | 4820  | 0.000 | 5600  | 0.424 |
| 3600  | 0.991 | 4280  | 0.000 | 4840  | 0.000 | 5620  | 0.213 |
| 3620  | 0.973 | 4300  | 0.000 | 4860  | 0.000 | 5640  | 0.000 |
| 3640  | 0.940 | 4320  | 0.000 | 4880  | 0.000 | 5660  | 0.000 |
| 3660  | 0.816 | 4340  | 0.000 | 4900  | 0.000 | 5680  | 0.000 |
| 3680  | 0.356 | 4360  | 0.000 | 4920  | 0.000 | 5700  | 0.000 |
| 3700  | 0.000 | 4380  | 0.000 | 4940  | 0.000 | 5720  | 0.000 |

4. REVIEW OF SOME OTHER NATURAL uvby SYSTEMS

Manfroid (1984) was the first to use synthetic photometry to explore the systematic effects that different instrumental system passbands have on uvby photometry. This was further discussed by Manfroid & Sterken (1987). We decided to use the NGSL spectrophotometric data to examine two widely used natural uvby systems, the four-channel spectrograph photometers.
(Helt et al. 1987) and that of Cousins (1987), in order to explore the systematic differences that could be expected between their instrumental systems and that presented in this article as representing the standard system. The photonic passbands of Helt et al. (1987) are plotted in Figure 1 and listed in Table 3 (the narrow spike in the published Helt et al. u passband has

**Fig. 8.**—Synthetic $\Delta(u - v)$ regressions for the natural four-channel system (Helt et al. 1987) (left) and Cousins (1987) (right). Dwarfs (dots), giants (open circles). See the electronic edition of the PASP for a color version of this figure.

**Fig. 9.**—Synthetic $\Delta(v - b)$ regressions for the natural four-channel system (Helt et al. 1987) (left) and Cousins (1987) (right). Dwarfs (dots), giants (open circles). See the electronic edition of the PASP for a color version of this figure.
been smoothed over). In Figures 8 and 9 we show the computed differences in the $u/v$ and $v/b$ colors plotted against $b/y$ for the NGSL spectra. The division between dwarfs and giants in these plots was made at $\log g = 3.5$; higher-gravity stars are plotted as dwarfs, and lower-gravity stars are plotted as giants. The total range of the vertical scales of the two plots in each figure is the same.

The differences shown in the plots are very similar to those indicated by Olsen (1983), Cousins (1987), Manfroid (1984), and Manfroid & Sterken (1987). It is interesting to see the dwarf-giant separation for the cooler stars and the increase in scatter for the cooler giants.

The effect of the narrow $v$ band ($\sim 110$ Å FWHM) reported by Eggen (1976) was also investigated. An Eggen-type $v$ band was constructed by simply scaling the half-width of the standard band and keeping the same central wavelength. Figure 10 shows the computed difference in the measured $v$ magnitude plotted against $b/y$ and $\beta$. Large differences are seen for the hotter stars (due to the strength of the H$\delta$ line) and for the cool giants and dwarfs (due mainly to the atomic and molecular features).

As pointed out by Manfroid & Sterken (1987), these comparisons underline the difficulties that observers with non-standard passbands experience when trying to standardize their internally precise $uvby$ photometry.

5. SUMMARY

We have derived passbands for the $uvby$ system using the KPNO No. 1 filter transmissions of Matsushima (1969) and Crawford & Barnes (1979) convolved with the cathode sensitivity function of a 1P21 photomultiplier tube and an extinction of 1.2 air masses. These were converted to photonic passbands by dividing by the wavelength and then renormalized. They are listed in Table 1 and shown in Figure 1.

Initial AB magnitude $uvby$ zero points were derived from the stis005 spectrum of Vega. Synthetic photometry was then carried out on the extensive NGSL and MILES spectrophotometric catalogs and compared with the observational data in the homogenized Hauck & Mermilliod (1998) catalog. Excellent linear fits with near-unity slopes were made to the synthetic-observational regressions, showing how well the passbands represent the standard system. The coefficients of the fitted lines are given in Table 2, and the equations from the NGSL stars should be used to produce standard photometric values from synthetic photometry of observed spectrophotometric fluxes or model atmosphere fluxes.

Some nonstandard passbands of two well-defined natural $uvby$ systems were also synthesized and shown to produce similar systematic differences to those reported by the users. These effects limit the accuracy with which transformations to the standard system can be made, mainly for the cooler stars and the hotter reddened stars. The narrow $v$ band used by Eggen (1976) and others was shown to produce the largest systematic differences and supports Eggen’s decision to not standardize his $M_1$ and $C_1$ photometry.

However, in spite of these limitations, observers have generally been successful with transforming their photometry onto
the standard system, and Hauck & Mermilliod (1998) have been successful with producing a very useful homogenized uvby catalog. Hopefully, the revised passbands and transformation equations presented here will enable more reliable theoretical calibrations of Strömgren indices to be made using model atmosphere fluxes.

I wish to thank William Schuster for very helpful correspondence concerning the history and operation of the four-channel spectrograph photometers and the referee Chris Sterken for many suggestions that improved the article. Vizier-R, Simbad, TopCat, and Kaleidagraph were used in preparing this article.

REFERENCES

Bessell, M. S. 1979, PASP, 91, 589
———. 1983, PASP, 95, 480
Bessell, M. S., & Murphy, S. J. 2011, PASP, submitted
Clem, J. L., VandenBerg, D. A., Grundahl, F., & Bell, R. A. 2004, AJ, 127, 1227
Cousins, A. W. J. 1987, SAAO Circ. 11, 93
Crawford, D. L., & Barnes, J. V. 1979, AJ, 75, 978
Eggen, O. J. 1976, PASP, 88, 732
Hauck, B., & Mermilliod, M. 1998, A&AS, 129, 431
Heap, S. R., & Lindler, D. 2007, in IAU Symp. 241, Stellar Populations as Building Blocks of Galaxies (Cambridge: Cambridge Univ. Press), 95
Helt, B. E., Franco, G. A. P., & Florentin Nielsen, R. 1987, in ESO Workshop on SN 1987A (Garching: ESO), 89
Kurucz, R. L. 1987ApJS, 40, 1

Maiz Apellaniz, J. 2006, AJ, 131, 1184
Manfroid, J. 1984, A&A, 141, 101
Manfroid, J., & Sterken, C. 1987, A&AS, 71, 539
Matsushima, S. 1969, ApJ, 158, 1137
Olsen, E. H. 1983, A&AS, 54, 55
———. 1993, A&AS, 102, 89
Önehag, A., Gustafsson, B., Eriksson, K., & Edvardsson, B. 2009, A&A, 498, 527
Relyea, L. J., & Kurucz, R. L. 1978, ApJS, 37, 45
Sanchez-Blazquez, P., Peletier, R. F., Jimenez-Vicente, J., Cardiel, N., Cenarro, A. J., Falcon-Barroso, J., Gorgas, J., et al. 2006, MNRAS, 371, 703
Schuster, W. J., & Nissen, P. E. 1988, A&AS, 73, 225
Strömgren, B. 1966, ARA&A, 4, 433
Young, A. T. 1963, Appl. Opt., 2, 51