CORRECTION OF UBV PHOTOMETRY FOR EMISSION LINES

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Abstract. We investigate the effect on $U, B, V$ magnitudes of the removal of emission lines from the spectra of some symbiotic stars and novae during their nebular phases. We approach this problem by the precise reconstruction of the composite UV/optical continuum and the line spectrum. The corrections $\Delta U$, $\Delta B$ and $\Delta V$ are determined from the ratio of fluxes with and without emission lines. We demonstrate the effect for symbiotic nova V1016 Cyg during its nebular phase. We find that about 68%, 78% and 66% of the observed flux in the $U$, $B$ and $V$ filters is radiated in the emission lines. The effect should be taken into account before using the observed color indices of emission-line objects for diagnosis of their radiation in the continuum.

Key words: techniques: photometric – stars: emission line – stars: binaries, symbiotic

1. INTRODUCTION

Photometric measurements in the standard $U, B, V$ filters are often used to analyze radiation in the continuum of many kinds of stellar objects. A diagnosis by the $U - B$, $B - V$ diagram is frequently applied to compare the observed color indices to those of the continuum radiation from main-sequence stars, supergiants, a black-body and/or a nebula. However, the true continuum is often affected by the line spectrum, which thus requires corrections of magnitudes and color indices before studying the continuum radiation.

In this paper we investigate the effect of the removal of emission lines from the spectrum on $U$, $B$, $V$ magnitudes. However, a strong variation of the emission spectrum due to the activity, large differences between individual objects and a complex profile of the
true continuum for emission-line objects preclude a simple solution. Hitherto, this problem has been approached only by a few groups of authors and without giving any concept for a general application (see, e.g., Fernández-Castro et al. 1995).

Here we estimate the corrections for $U,B,V$ magnitudes due to emission lines by exact calculations of the predicted spectrum. We demonstrate this effect in the case of symbiotic nova V1016 Cyg, whose spectrum is very rich in strong emission lines during its nebular phase.

2. ANALYSIS

2.1. The method

We are trying to determine the ratio of the continuum with the superposed emission lines to the line-removed continuum at all relevant wavelengths. For this we need the profile of the continuum and the emission-line spectrum obtained (in the ideal case) simultaneously with the photometric observations.

To quantify the effect of emission lines on the $U,B,V$ measurements, we express the observed flux in the form

$$F_{\text{obs}}(\lambda) = F_{\text{cont}}(\lambda)(1 + \epsilon(\lambda)),$$

where $F_{\text{cont}}(\lambda)$ is the true continuum (i.e. line-removed continuum) and $\epsilon(\lambda)$ represents the emission-line spectrum in units of the continuum at the wavelength $\lambda$. Then the magnitude difference, $\Delta m$, between the observed magnitude, $m_{\text{obs}}$, and the magnitude of the true continuum, $m_{\text{cont}}$, can be expressed as

$$\Delta m = m_{\text{obs}} - m_{\text{cont}} = -2.5 \log \left[ \frac{\int F_{\text{cont}}(\lambda) S(\lambda)(1 + \epsilon(\lambda)) \, d\lambda}{\int F_{\text{cont}}(\lambda) S(\lambda) \, d\lambda} \right],$$

where $S(\lambda)$ is one of the response functions of the $UBV$ system. Further, we approximate the emission-line spectrum with an ensemble of Gauss functions, $G_i$, as

$$\epsilon(\lambda) = \sum_i G_i(\lambda; \lambda_i, I_i, \sigma_i),$$

where $\lambda_i$ is the wavelength of the $i$-th line, $I_i$ is its maximum in units of the local continuum and $2\sigma_i$ is its FWHM. According to the relation (2), the removal of emission lines from the spectrum gives fainter.
magnitudes at all wavelengths. The main difficulty in calculating the corrections $\Delta m$ is connected with reconstruction of the continuum profile, $F_{\text{cont}}(\lambda)$, which can be rather complex in the case of the composite continuum of symbiotic stars. We introduce briefly this problem in Sect. 2.3. We reconstructed the line spectrum, $\epsilon(\lambda)$, according to parameters available in the literature (fluxes and the continuum level). An example is given in Sect. 2.4.

2.2. Calculated $U$–$B$ and $B$–$V$ color indices

Color indices in the $U,B,V$ system can be calculated from energy distribution curve once the response functions $S(\lambda)$ of the system are known. Theoretical color indices $(U-B)_0$ can be calculated by the equation

$$(U-B)_0 = -2.5 \log \left[ \int F(\lambda)S_U(\lambda) \, d\lambda / \int F(\lambda)S_B(\lambda) \, d\lambda \right]. \quad (4)$$

A similar equation is used for the $(B-V)_0$ index. The aim is to obtain such $U-B$ and $B-V$ indices, which would predict the observed colors for real stars of known energy distribution. This task requires additional color equations, which are used to convert theoretical calculations based on the adopted $S(\lambda)$ to the empirical $U,B,V$ system. Matthews & Sandage (1963) derived the following equations

$$B-V = 1.024(B-V)_0 + 0.81, \quad U-B = 0.921(U-B)_0 - 1.308, \quad (5)$$

which correspond to $S(\lambda)$ from their Table A1. Later on, Ažusienis & Stražys (1969) suggested the following relations

$$B-V = (B-V)_0 + 0.67, \quad U-B = (U-B)_0 - 1.33, \quad (6)$$

for their set of the revised response functions (see their Table 1). We compared both transformations on the example of color indices of black bodies of different temperatures (Figure 1). Both transformations give very close values, and in this paper we use only the Matthews & Sandage (1963) equations.

2.3. The composite continuum

We reconstruct the continuous radiation, $F_{\text{cont}}(\lambda)$, of symbiotic binaries by a three-component model, which consists of two stellar components of radiation, the hot and the cool stars, and the nebular
Fig. 1. Comparison of the blackbody color indices calculated by Eq. (5) (the solid line, Matthews & Sandage 1963) and Eq. (6) (the dashed line, Ažusienis & Stražys 1969).

radiation from the ionized circumbinary medium (e.g., Nussbaumer & Vogel 1989). We approach this problem with the aid of low-resolution IUE spectra and broad-band infrared photometry. The latter was approximated by synthetic spectra for red giants according to models of Hauschildt (1999) to get the infrared stellar continuum. Then, on the basis of such defined continuum, we applied the three-component model of the radiation of symbiotic stars to get the profile of the continuum in between these regions (see Skopal 2001, 2003 for details).

2.4. The emission-line spectrum

Figure 2 shows the example of the $\epsilon(\lambda)$ function from Eq. (1), which represents the emission-line spectrum of the symbiotic nova V1016 Cyg. To reconstruct this function we used emission-line fluxes published by Schmid & Schild (1990) (hereafter SS90). The spectrum was taken on 15 Nov. 1987 at the INT telescope.

3. THE EXAMPLE OF V1016 Cyg

V1016 Cyg is a symbiotic nova, which erupted in 1964 when it brightened by about 5 mag in the optical and has continued a very slow decrease of its brightness (Parimucha et al. 2000). It belongs to the D-type symbiotic stars (with strong IR dust emission) and contains a Mira variable as the cool component (SS90 and references therein). According to the ultraviolet (IUE) and optical (INT) observations, the near-UV/optical spectral region was dominated by the nebular continuum superposed with strong emission lines at high excitation/ionization degrees (SS90).

To reconstruct the optical continuum of V1016 Cyg we used the IUE spectra SWP 24655 and LWP 04959 taken on 10 Dec. 1984, and the synthetic spectrum for a red giant with $T_{\text{eff}} = 3100$ K and $\log g = 0.5$ (Hauschildt et al. 1999). The latter was scaled to the observed flux in the $J$-band, which is assumed to be free of any dust emission. The emission-line spectrum is shown in Figure 2. All observations were dereddened for interstellar extinction with $E_{B-V} = 0.28$ (SS90).
Fig. 2. Function $\epsilon(\lambda)$ for the symbiotic nova V1016 Cyg, which represents its emission-line spectrum in units of the continuum. Dotted lines show normalized response functions of the $U, B, V$ filters.

Fig. 3. Reconstructed SED in the near-UV/optical continuum of the symbiotic nova V1016 Cyg. The solid thin line represents radiation from the hot object ($T_h = 150 000$ K), the dashed line represents the radiation from the nebula ($T_e = 16 800$ K) and the solid thick line represents the resulting modeled continuum. The radiation from the giant was compared with the synthetic spectrum and scaled to the flux in the $J$ band (see the text). The emission-line spectrum was introduced in Fig. 2. Full circles represent fluxes obtained from the broad-band photometry. Triangles are the $U, B$ and $V$ magnitudes corrected for the emission lines.

The results are shown in Figure 3. Our model confirms a strong contribution of the nebula in optical wavelengths. Applying our procedure described in Section 2, we found that the removal of emission lines makes the star fainter by 1.23, 1.67 and 1.18 mag in the $U, B$ and $V$ passbands, respectively. This means that in these passbands V1016 Cyg emission lines contain about 68%, 78% and 66% of the total light. The corrected fluxes perfectly fit the predicted continuum. The effect is different in different passbands, which results in the change of color indices. Eqs. (4) and (5) give the following values of color indices: $(U - B) = -1.27$, $(B - V) = +0.03$ for the observed
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spectrum (including lines) and $(U - B)_{\text{cont}} = -1.68$, $(B - V)_{\text{cont}} = +0.53$ for the model continuum. This results in a rather significant change of color indices: $\Delta(U - B) = 0.41$ and $\Delta(B - V) = -0.50$. It is necessary to remove these color excesses due to emission lines from color indices before using them for modeling the star system.

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