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Radial velocity determination by CCF using a synthetic spectrum as the template and detecting component spectra in SB1 binaries

J. Zverko[1], **J. Žižňovský**[1], **Z. Mikulášek**[2], **I.Kh. Iliev**[3]

[1] *Astronomical Institute of the Slovak Academy of Sciences 059 60 Tatranská Lomnica, The Slovak Republic*

[2] *Institute of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, CZ-611 37 Brno, The Czech Republic*

[3] *National Astronomical Observatory, Bulgarian Academy of Sciences, P.O. Box 136, BG-4700 Smolyan, Bulgaria*

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Abstract. Radial velocity determination is one of the basic methods of learning on stars and their systems. We aim at utilizing a computerized method for radial velocity measurements from spectra on electronic and photographic media. We compute the crosscorrelation function of an observed and synthetic spectrum. Applicability of the method is documented on electronic spectra of the double star V624 Her as well as photographic spectra of the binary AR Aur. The feasibility of the method for detecting of component spectra is demonstrated on systems HD 861 and HD 71973. We also show a possible way of using wide features such as hydrogen lines in early type stars in radial velocity determination.

Key words: methods: spectroscopy – methods: numerical – stars: individual: V624 Her, HD 861, HD 71973, AR Aur

1. Introduction

Many sophisticated methods exist for radial velocity (RV) determination, among them those based on instruments especially designed for such measurements (e. g. CORAVEL, Baranne et al. 1979, Queloz 1995) utilizing crosscorrelation of a star's spectrum with a suitably selected template spectrum. They have been further upgraded with a digital processing (Baranne et al. 1996). Griffin et al. (2000) provided a detailed study of various approaches to the matter and evaluated their feasibility for stars of a variety of spectral classes and kinds. One of the advantages of the method introduced in their paper consists in that it makes use of standard spectrograms taken for general tasks of spectroscopic studies. Zucker & Mazeh (1994) developed a two-dimensional correlation algorithm TODCOR to derive radial velocities from spectra of an SB2 star, especially suitable for binary spectra with small velocity diferences. Besides these cross-correlation techniques, disentangling methods exist giving radial velocities and spectra of individual components simultaneously (Simon & Sturm 1994, Hadrava 1995.)

In this paper we present a method that uses a synthetic spectrum as the template to be numerically crosscorrelated with the observed spectrum of a star. The synthetic spectrum is computed with values $T_{\rm eff}, \log\,g$ either estimated roughly from a spectral type or more precisely derived by a preceding analysis. In Section 2 we describe the method and derive the error of the resulting values. In Sec. 3 we demonstrate the application of the method to spectra, either CCD or photograpic, of wide SB2 systems. In Sec. 4 we deal with using wide features such as Balmer lines, while in Sec. 5 we show how to detect weak component spectra in systems fromerly known as single-lined. As in these cases one does not a-priori know the spectral type of the component spectrum we suggest using the unique pattern of the spectrum of iron as a template.

2. The method

It is supposed that the record of a spectrum has already been corrected for trends and large-scale distortion, photographic spectrograms must be digitized previously. The spectrum has not to be rectified to the continuum, neither transmission of a photographic spectrogram does not have to be transformed to intensities. However, transformation of densities to intensities increases the attainable accuracy of the resulting value of radial velocity. Special attention must be paid to spectra with strong wide features such as e. g. Balmer lines in the violet-blue region in A-stars. These features should be 'rectified' so that the wings are considered as continuum except for a close vicinity of the central wavelength. Treating the central part of Balmer lines themselves is described in Section 4.

Since the RV value is proportional to the ratio $\Delta\lambda/\lambda$, it is desirable to convert the wavelength to the logarithmic scales. Consequently, the observed spectrum is first transformed into the format where intensities are linearly interpolated in K equidistant steps in $\ln\lambda$, $\{I_i^{\rm obs}\}$. The synthetic spectrum is computed for the same net of the wavelengths points, $\{I_i^{\rm syn}\}$. Then the coefficient of correlation, Pearson's r, of the two files shifted mutually in $\ln\lambda$ by j steps $\Delta\ln\lambda$, is computed according to formula

$$r_j = \frac{\sum\limits_{i=1}^{K-j}\left(I_i^{\rm syn} - \overline{I^{\rm syn}}\right)\left(I_{i+j}^{\rm obs} - \overline{I^{\rm obs}}\right)}{\sqrt{\sum\limits_{i=1}^{K-j}\left(I_i^{\rm syn} - \overline{I^{\rm syn}}\right)^2 \sum\limits_{i=1}^{K-j}\left(I_{i+j}^{\rm obs} - \overline{I^{\rm obs}}\right)^2}}. \tag{1}$$

This is repeated $2\,n+1$ times so that a maximum r_j occurs within $(-n\,\Delta\ln\lambda$, $n\,\Delta\ln\lambda)$, representing the interval of radial velocities, ΔRV, in which the cross-correlation is investigated, $n = 2\,\Delta RV/(c\,\Delta\ln\lambda)$. The Pearson's r_j acquires values $\in < -1, +1 >$ and is symmetrical for single-lined spectra. The crosscorrelation function (CCF) is displayed as a sequence of r_j-s. It can be well fitted with a gaussian to calculate the value of RV corresponding to the CCF maximum. When transforming the spectra into equidistant steps, the wavelength of the first blue point in both spectra, i. e. the synthetic and the observed ones, must be selected equal to obtain a correct difference of RV between them. Interactive FORTRAN codes were written to handle the procedures and run under Linux.

The possible sources of errors of a resulting value of RV were analyzed in details by Griffin et al. (2000), who also evaluated possible effects if the template spectrum differs to some extent from the real one, as it can occur in the case of chemical peculiarities. We are interested in only those errors arising from the CCF method described here. Queloz et al. (1995) give the error introduced by the signal noise to be proportional to the S/N ratio, the minimum value of the crosscorrelation function (in their case similar to convolution) and the number of lines in the template. For high $S/N \approx$ of hundreds, high resolution ($\approx 20\,000$) CCD spectra used in this work we obtain the error of $\approx 5\,\mathrm{m\,s^{-1}}$, for photographic spectra ($S/N \approx$ of tens) the error is $\approx 50\,\mathrm{m\,s^{-1}}$. Their formulas, however, were derived by means of Monte-Carlo simulations for very low, $S/N \approx$ unity, spectra. Lehman et al. (2006) for high resolution spectra, $S/N = 45\,000 - 63\,000$, and 2500 Å wide window mentioned accuracy 62 $\mathrm{m\,s^{-1}}$.

To estimate the accuracy of the RV value determined by the CCF method we deduce a formula

$$\delta RV = \frac{c\ \sigma(I^{\mathrm{syn}})}{\sqrt{\overline{\left(\frac{\partial I^{\mathrm{syn}}}{\partial(\ln\lambda)}\right)^2}}} \sqrt{\frac{1}{N}\left(\frac{1}{r_{\max}^2} - 1\right)}, \tag{2}$$

where c is the speed of light, $\sigma(I^{\mathrm{syn}})$ is the standard deviation of the intensity of the template spectrum, N is the number of wavelength points (pixels) of the observed spectrum, and $r_{\max}$ is the maximum value of the CCF. The first term expresses the effective width of spectral features in the template spectrum and depends namely on the rotational velocity of the star and the saturation of the particular region of the spectrum by spectral lines. Typically, it corresponds to several tens of $\mathrm{km\,s^{-1}}$. The second term is related to the measure of linear relationship of the observed and synthetic spectrum, and the number of wavelength points in the observed spectrum.

For a window of a single-lined spectrum 85 Å long with 844 pixels 0.1 Å wide we estimate $\delta RV = \pm 0.82\,\mathrm{km\,s^{-1}}$.

For double-lined spectra the formally estimated error is larger as the resemblance of a single-lined synthetic spectrum with a double-lined observed spectrum is poorer (or the value $r_{\max}$ is smaller) due to the number of lines of the second component not obeying the fit. This is fully in accordance with the findings of Griffin et al. (2000) that the closer the reference spectrum as a mask is used the better accuracy is achieved.

Other possible formal estimate of the accuracy can be calculated using the S/N ratio of the observed spectrum and the size of a pixel expressed in λ or RV. The observed spectrum consists from a signal and a noise. There are k significant points (pixels) of the signal that create the profiles of all the lines in the window and determining the value of CCF, while the photon noise superposed on the continuum does not contribute. We count the points whose intensity is less than $1 - (S/N)/2$ (note that we deal with absorption lines here), to avoid safely the points belonging to the noise of continuum. The size of the pixel can be considered as a standard deviation, i. e. "the mean error of one measurement". Then the mean error of the average, the r.m.s., is obtained when dividing the former by the root of $k-1$. For the same spectrum as used in the example given in the previous paragraph we obtain $\delta RV = \pm 0.79\,\mathrm{km\,s^{-1}}$.

Once the spectral type and luminosity of a star is known, the synthetic spectrum with an estimated $T_{\mathrm{eff}}, \log g$ can be computed. In principle, an elementary synthetic spectrum with standard abundances, some mean value of microturbulence and a roughly guessed $v \sin i$ value is sufficient to derive the value of RV. However, the more accurately the parameters mentioned above are derived the higher value of the CCF at its maximum is reached.

If the binary is of the SB2-type, the synthetic spectra for each of the components should be computed. The synthetic spectrum of one of the binary components is crosscorrelated with the observed spectrum, resulting in the best value of its RV. The same is performed with the synthetic spectrum of the other component.

Since spectral types of components of double-lined binaries differ as a rule only within a few subclasses, and if the extent $(-n\,\Delta \ln \lambda, n\,\Delta \ln \lambda)$ tested is wide enough, a secondary maximum in the CCF will be seen at the position corresponding to the RV of the second star. In the case the observed spectrum was taken near the maximum elongations, the CCF maxima are far from each other. Then the two values of RV can be read out simply as the positions of the maxima (see Fig. 2). In the case the spectra were taken near the phases of conjunctions, the CCF maxima get closer and each maximum is influenced by the neighbour. Now individually computed synthetic spectra for each component help to minimize the interference. The correct values of RV should be derived by fitting the function with two Gaussians simultaneously (see Fig. 3). Since the width of the CCF profiles depends on the width of the spectral lines both in the template and real spectrum, the interference becames worse for spectra with lines broadened due to a high value of $v \sin i$. Consequently, the resolution given by the CCF is lower. The problem and its solution is discussed in details by Rucinski (2002). When using the crosscorrelation method discussed here, unwidened synthetic spectra may increase the separation of the CCF maxima. In Fig. 1 the radial velocity curve of the binary V624 Her is shown. The old measurement by Popper (1984) as well as our CCF determination of the radial velocities from new spectra are brought together.

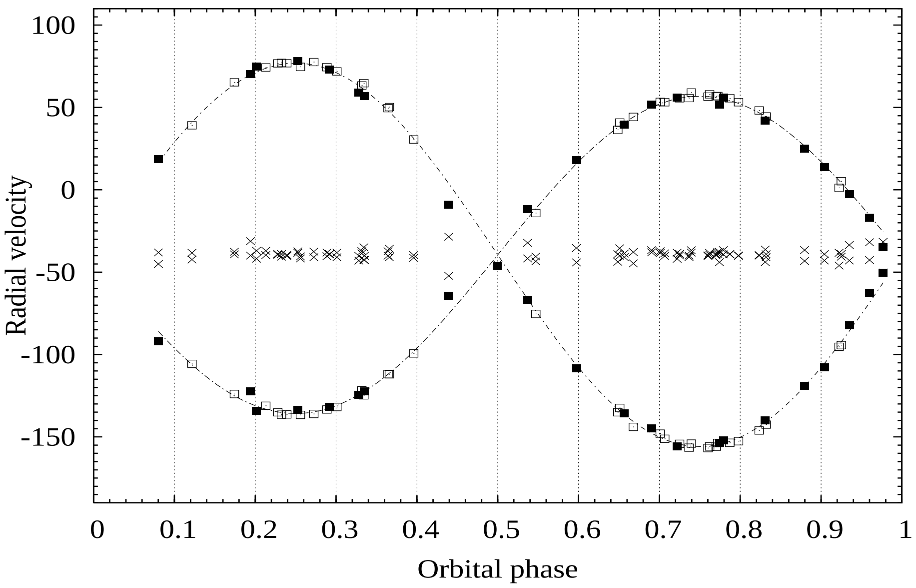

Figure 1. The radial velocity curve of V624 Her. Open symbols: values from 1972-1982 by Popper (1984), full symbols: values from 2000-2005 measured by CCF, crosses: deviations from the curves calculated with zero eccentricity.

When detecting unresolved components we face the task to crosscorrelate a spectrum of an unknown spectral type. Though the crosscorrelating a synthetic spectrum with well defined atmosphere parameters results in a more pronounced CCF, a simpler pattern of a synthetic spectrum may offer an easier way to identify coincidences. For example, the iron spectrum represents such a simpler and unambiguous pattern. We computed a synthetic spectrum with iron lines only because these are the most numerous in the spectra of B - A stars. We show applicability of this way, too.

The synthetic spectra in this study were computed with the SYNSPEC code, Hubeny et al. (1994) modified by Krtička (1998). The line lists were extracted from the VALD database, Kupka et al. (1999).

3. Spectra of known SB2 binaries

3.1. CCD spectra of V624 Her

For the first time we used the method when analyzing the spectra of the SB2 binary V624 Her obtained with two CCD cameras in the Main Stellar Spectrograph of the 6-m telescope, Special Astrophysical Observatory, Russia (SAO),

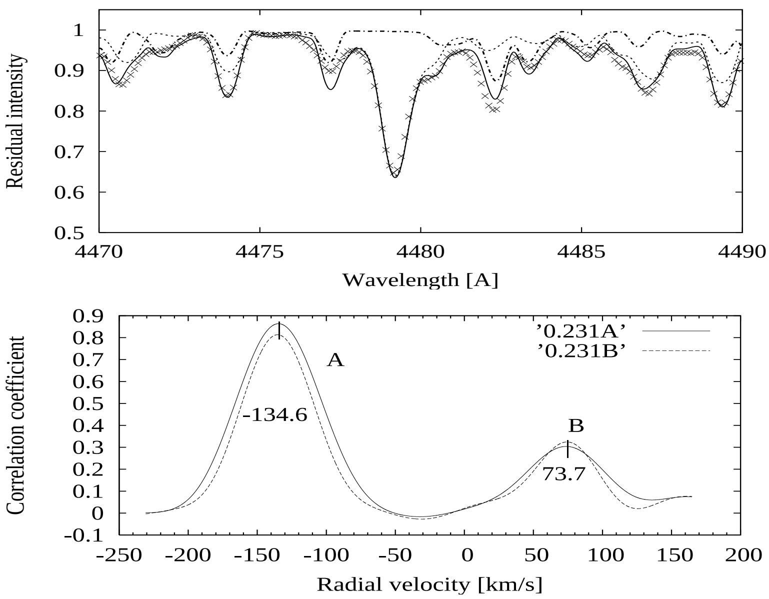

Figure 2. Top: A section of the spectrum of V624 Her around Mg II 4481 Å, orbital phase = 0.231. The synthetic components are shifted to fit the individual RVs and summed with L_s/L_p = 0.48. Dotted – synthetic primary, dash-dotted – synthetic secondary, full – synthetic summed, crosses – observed spectrum. **Bottom:** The CCF for the orbital phase = 0.231. Full line – the primary synthetic spectrum, dotted – the secondary one. As $T_{\rm eff}$-s differ little only two maxima are found no matter which of the synthetic spectra are crosscorrelated with the observed one. The small temperature difference results in the small differences in the shapes.

where special codes for primary reductions of CCD spectrograms are used instead of the IRAF package. Two cameras were used giving R = 16 000 and 19 000 at wavelength 4550 Å. The S/N was mostly better than 300.

V624 Her (HR 6611, HD 161321) is an eclipsing SB2 binary with Am components. It was well studied e. g. by Popper (1984) who, among others, determined the luminosity ratio of the components outside eclipses (L_s/L_p = 0.48 for the blue region) and effective temperatures and surface gravities $T_{\rm eff}$ = 8150 K, $\log g$ = 3.83 for the primary and $T_{\rm eff}$ = 7950 K, $\log g$ = 4.02 for the secondary component. With these parameters we interpolated models of atmospheres within the "New grids of ATLAS9 atmospheres" (Heiter et al. 2002), derived the abundance and micorturbulence values and computed synthetic spectra of the both components. Note that the synthetic spectrum should be reduced by the ratio of a corresponding component luminosity. In our case this is done (in terms $L_p + L_s = 1$) simultaneously when transformed to the logarithmic

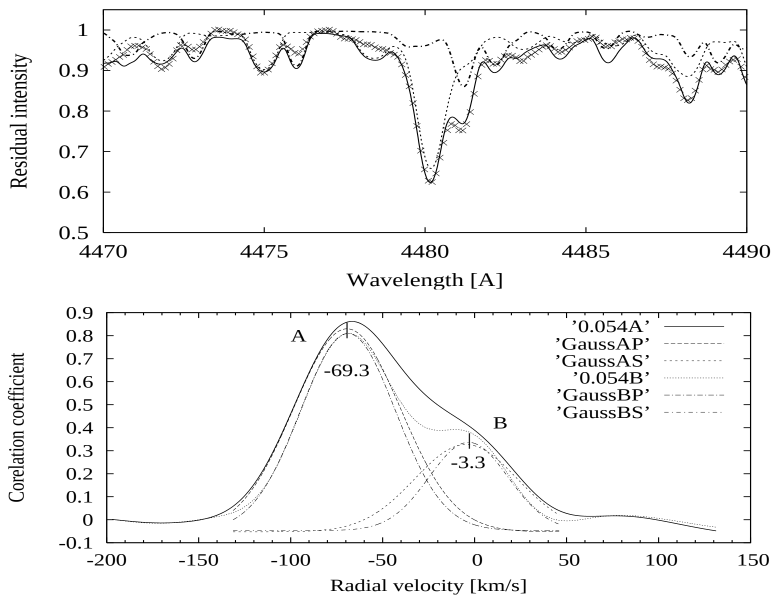

Figure 3. Top: A section of the spectrum of V624 Her around Mg II 4481 Å, orbital phase = 0.054. The synthetic components are summed with $L_\mathrm{s}/L_\mathrm{p} = 0.56$ corresponding to the partial eclipse at this phase. The legend is the same as in Fig. 2. **Bottom:** The CCFs for the orbital phase = 0.054. Full line '0.054A'- the CCF with synthetic spectrum of the A-component; '0.054B'- the CCF with synthetic spectrum of the B-component. 'GaussAP' and 'GaussAS'- two gaussians fitted to '0.054A'; 'GaussBP' and 'GaussBS'- two gaussians fitted to '0.054B'. Resulting values $RV = -69.30\,\mathrm{km\,s^{-1}}$ read from 'GaussAP' for the primary and $RV = -3.3\,\mathrm{km\,s^{-1}}$ read from 'GaussBS' for the secondary are accepted.

wavelength scale. In Figures 2 and 3 we display a section of the spectrum at two different orbital phases and corresponding CCFs. The maxima of the CCF corresponding to the primary and secondary binary component are fairly apart from each other at the orbital phase 0.231, while they overlap at the phase 0.054. In the latter case fitting with two gaussians by means of optimalization was used to extract the radial velocities of the components. Note also the different shape of the two CCFs in the vicinity of the second component that is due to the small difference in the spectral types of the binary components.

3.2. Photographic spectra of the eclipsing binary AR Aur

AR Aur (HR 1728, HD 34 364) is an eclipsing binary with CP components (Chochol et al. 1988, Khokhlova et al. 1995). Photographic spectra were obtained with

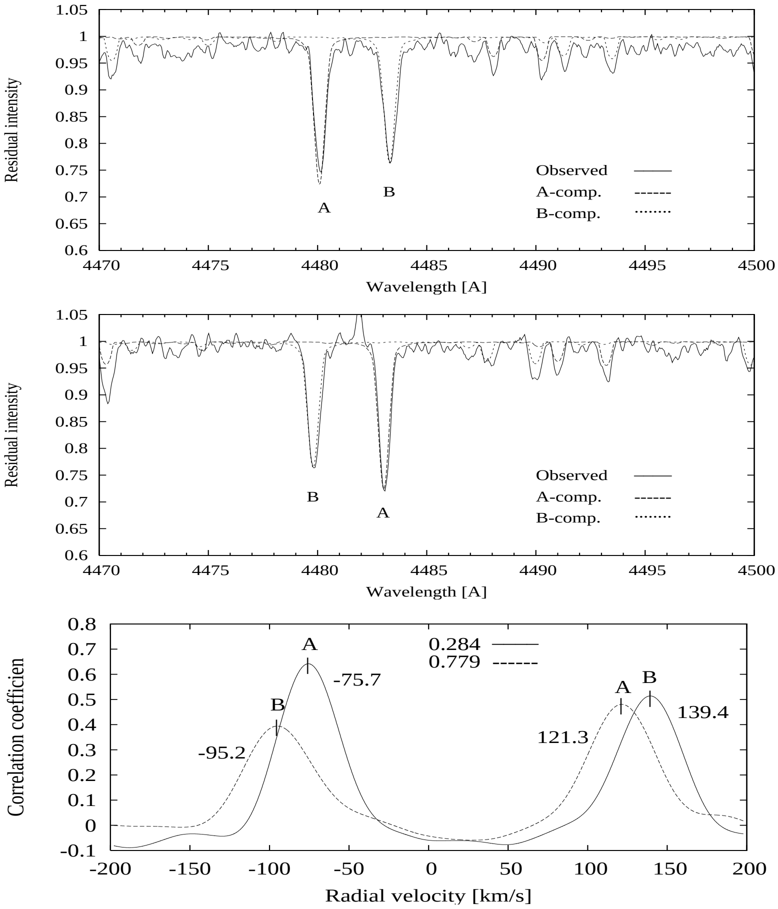

Figure 4. A section of the spectrum of AR Aur around Mg II 4481 Å, orbital phase = 0.284 **top**, and 0.779 **mid**. The synthetic components are shifted to proper radial velocities and summed with $L_{\rm s}/L_{\rm p}$ = 0.87 (Nordström & Johansen 1994). **Bottom:** AR Aur, the CCF in two opposite orbital phases 0.284 and 0.779.

the 6-m BTA reflector at SAO in November 1986 and reduced with the PDS microdensitometer at the Royal Greenwich Observatory by V.L. Khokhlova and R.E.M. Griffin (Khokhlova et al. 1995). The reciprocal dispersion of the spectra was 1.7 Å mm^{-1} and the microdensitometric tracing sampled the spectra in steps of 0.053 Å. The spectra around Mg II 4481 Å in orbital phases 0.284 and 0.799 are shown in Fig. 4. The synthetic spectra were computed for $T_{\rm eff} = 10\,950$ K, $\log g = 4.33$, $\xi_{\rm turb} = 0.5$ km s^{-1} and $v \sin i = 21.8$ km s^{-1} for the primary (A) component and $T_{\rm eff} = 10\,350$ K, $\log g = 4.28$, $\xi_{\rm turb} = 0.5$ km s^{-1} and

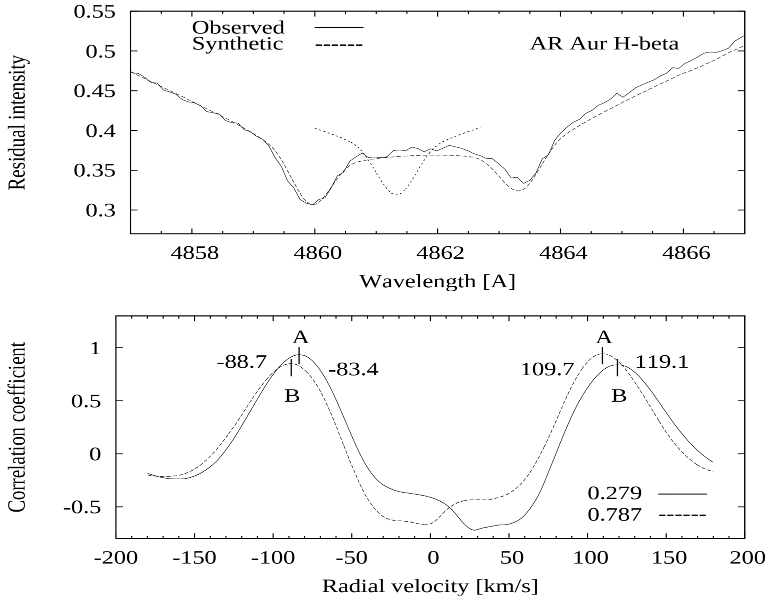

Figure 5. Top: A section of the spectrum of AR Aur around centre of H_β. The segment which is crosscorrelated with observed profile is shown dotted in its position $RV = 0$. **Bottom:** CCF for crosscorrelating of the central peak of the synthetic profile of H_β. Negative values of CCF correspond to the inverse appearance of the synthetic peak and the dip between the two observed peaks as shown on the upper panel. Values of corresponding RV are quoted.

$v \sin i = 22.3\,\mathrm{km\,s^{-1}}$ for the secondary (B) component according to Zverko et al. (1997) and Nordström & Johansen (1994). The relevant CCFs are displayed on Fig. 4 where also derived values of RV corresponding to the components are quoted.

4. Using Balmer lines

The Balmer lines in spectra of B – F stars are strong and have broad wings. When crosscorrelating such features, the relatively weak and narrow metallic lines contribute to the sum of deviations with a far less weight than the strong Balmers which dominate the shape of the CCF. This does not bring a problem when a symmetric observed line profile is crosscorrelated with a symmetric synthetic profile. A problem arises in the case of an SB2 binary with components having similar spectra. The profile of a Balmer line consists of two different contours, moreover summed according to luminosity ratio differing from unity, resulting thus in an asymmetric profile. Then in the crosscorrelation process

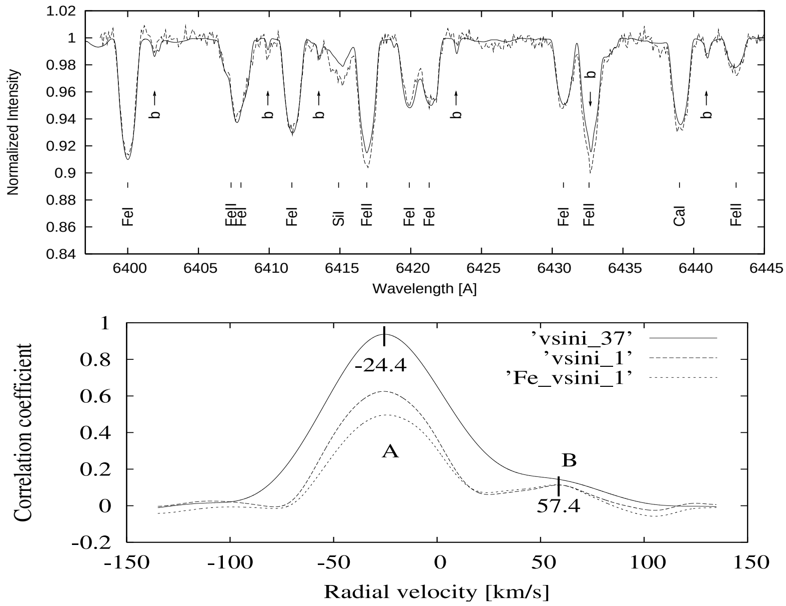

Figure 6. Top: A section of the spectrum of HD 861. **Bottom:** The CCF with various synthetic spectra: full line - complete linelist and $v \sin i = 37\,\mathrm{km\,s^{-1}}$, dashed line - a complete line list and $v \sin i = 1\,\mathrm{km\,s^{-1}}$, dotted line - Fe lines only and $v \sin i = 1\,\mathrm{km\,s^{-1}}$. $RV = -24.4$ and $57.4\,\mathrm{km\,s^{-1}}$ are derived for the first and second spectrum respectively.

we compare the two different profiles, obtaining as a result the value of RV corresponding to a centre of gravity of the observed profile and not to the correct RV. To make utilizing these spectra possible we select only a short segment of a synthetic spectrum, e. g. 2-3 Å wide, with the central peak of the line inside as shown on Fig. 5. Then this segment is correlated with the observed spectrum reaching the best fit of the central peaks. However, the accuracy of the RV derived is essentially lower, in agreement with the width of Balmer lines and the number of points in the correlated window.

5. Spectra of formerly known SB1 stars

5.1. CCD spectra of HD 861

In what follows we demonstrate the applicability of the method when detecting spectra of the so far unseen components.

Iliev et al. (2001), Budaj et al. (2003) and Iliev et al. (2006), in the frame of their observational program on Am stars in binary systems, have detected secondary and ternary spectra in a few binaries formerly known to be of the SB1 type.

HD 861 (SAO 11044, HIP 1063, BD +61 16, V=6.63) have been a well known SB1 binary classified by Slettebak & Nassau (1959) as A2 based on the Ca II – K line and as F2 based on metalic lines. Iliev et al. (2006) derived $T_{\rm eff} = 8250\,{\rm K}, \log g = 4.0$, $\xi_{\rm turb} = 2.3\,{\rm km\,s^{-1}}$and $v \sin i = 37$ km s^{-1} for the main component. They revealed weak narrow and moving features in spectra obtained between January 2001 and October 2004. The spectra were taken with the coudé spectrograph of the 2 m telescope of the National Astronomical Observatory (NAO) at Rozhen, Bulgaria. The resolution at 6400 Å was $R = 32\,000$, and the $S/N \approx 300$. One of the spectra is displayed in Fig 6.

First we used the synthetic spectrum computed with the temperature, gravity and $v \sin i$ as introduced above. Besides a clear maximum corresponding to the primary spectrum only a bump is indicated on the right wing of the CCF, see Fig. 6, bottom panel. When we used the same spectrum but widened rotationally to $1\,{\rm km\,s^{-1}}$ a secondary maximum at the position corresponding to $57.4\,{\rm km\,s^{-1}}$ emerged. The third CCF drawn with the dotted line in Fig. 6 belongs to the synthetic spectrum consisting only of iron lines. One can see that even in this simplified procedure not only the RV of the first component can be determined reliably but also the second maximum referring to the weak second spectrum can be visualized recognizably. The sensibility of the CCF with respect to the $v \sin i$ value shows that more values of rotational velocity should be tested.

5.2. CCD spectrum of HD 71973

HD 71973 (HR 3352) is an Am binary listed by Budaj (1996) in his study of the Am phenomenon and was observed in the frame of the above mentioned observational program on Am stars. Batten et al. (1989) give the orbital parameters and a spectral type A2 of the primary component, without a spectral type of the secondary component. Renson (1991) gives spectrum A3 (Ca II)–F0 (metalic lines). In the spectra obtained with the same instrument at NAO as mentioned in the previous paragraph Budaj noticed a possible third spectrum.

In this demonstration we used synthetic spectra with iron lines only for the secondary as well as for the primary component in order to keep equal conditions for indicating the CCF maxima. We used the model atmospheres from Heiter et al. (2002). The primary spectrum, quoted as A2, was computed with $T_{\rm eff} = 8250\,{\rm K}$, $\log g = 4.0$, $\xi_{\rm turb} = 0.5\,{\rm km\,s^{-1}}$ and $v \sin i = 30\,{\rm km\,s^{-1}}, 10\times$ enhanced iron abundance. The second spectrum quoted as F0 was computed for $T_{\rm eff} = 7250\,{\rm K}, \log g = 4.0$, $\xi_{\rm turb} = 0.5\,{\rm km\,s^{-1}}$ and $v \sin i = 10\,{\rm km\,s^{-1}}$.

Fig. 7 displays one of the observed spectra, referenced as 'ck3' (Top) in the log of observations, and the spectrum of the secondary drawn in the position indicated by the corresponding CCF. Fig. 7 (Middle) displays other observed spectrum, 'cw2', together with the spectra of the secondary and tertiary components shifted in RV to the positions indicated by the corresponding CCFs, Fig. 7, bottom panel.

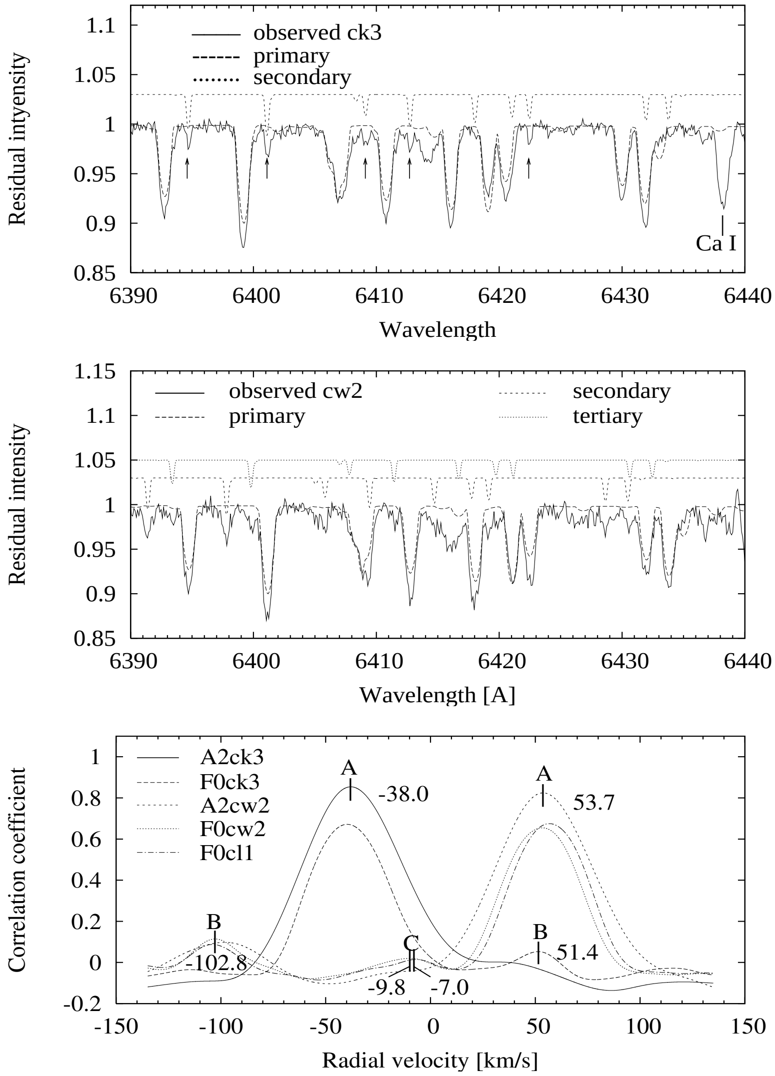

Figure 7. Top: A section of the spectrum HD 71973 'ck3' with synthetic iron spectra. The synthetic spectrum of the secondary is tentatively reduced to 0.2 in relative luminosity and shifted upward for clarity. **Middle:** A section of the spectrum HD 71973 'cw2' with synthetic iron spectra. The spectra of the secondary and tertiary are tentatively reduced to 0.2 and 0.15 in relative intensity and shifted upward for clarity. **Bottom:** CCFs for 2 spectra of HD 71973. While in the CCF-s for 'ck3' two maxima are present at $-38\,\mathrm{km\,s^{-1}}$ and $51.4\,\mathrm{km\,s^{-1}}$ in the 'cw2' and 'cl1' also a third maximum can be identified at positions -9.8 and $-7\,\mathrm{km\,s^{-1}}$, respectively. For simplicity, in the case 'cl1' only the CCF for F0 is shown here.

6. Summary

We elaborated a method for determining radial velocities by means of cross-correlation of the observed spectrum with a synthetic one as a template. We gave examples of using it on electronic as well as photographic spectra. We also derived a formula for estimating the accuracy of the method. We showed the applicability of the method to spectra of double stars either single-lined (SB1) or double-lined (SB2) ones. The method is also suitable for detecting faint component spectra, secondary in SB1 or tertiary in SB2 systems, without the need of detailed knowledge of the stellar parameters of a further component. A simplified way for recognition of a possible component in a spectrum using only iron synthetic spectra is also suggested. Exploring spectra with wide features, such as Balmer lines, is also proved as feasible.

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