Spectroscopically and Spatially Resolving the Components of Close Binary Stars
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Do our spectra match the requirements for a precise analysis of SB2s?

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Abstract. In the last decade of the 20th century, powerful techniques to resolve the spectra of multiple light sources into their components were developed. Non-physical undulations may appear in the resulting component spectra. These undulations may be triggered, at least partly, by systematic errors in input spectra. The whole data reduction process of echelle spectroscopy is critically reviewed with the purpose to encourage the user to evaluate, empirically, sources of systematic errors in spectra. Such checks should be done on extracted calibration and science spectra *before* normalising and combining single spectral orders. Furthermore, in cases where many spectra of an object will be combined in one analysis, a *differential* data reduction procedure is recommended.

1. Introduction

Cross-dispersed echelle spectrographs provide an efficient way to record high-resolution spectra over a large wavelength range in a single exposure on CCDs. The price to pay is the complex format, each spectral order being modulated strongly in intensity. The full spectra obtained by merging the normalised single orders are susceptible to minor non-physical undulations in the best case and to order merging signatures in many first-look data reduction pipelines.

Modern analysis techniques of composite stellar spectra exploit the Doppler information in various parts of the orbit to reconstruct the spectrum of each star. In case of a large number of input spectra, the random noise in the reconstructed component spectra is lower than it was in the input spectra. However, with many free parameters involved (somewhat more than the number of wavelength bins times the number of components), the systematic patterns in the component spectra are likely stronger than in the input data, and they can become the dominant source of error. Since the precision of Doppler measurements depends more strongly on spectral gradients than on signal-to-noise (S/N), the propagation of systematic errors mostly hampers the analysis of the component spectra for faint components and spectra with shallow lines.

This paper is organised as follows. An example of how systematic noise in input spectra could grow to an important level in the component spectra is presented in Sect. 2. An overview of sources of systematic errors in the data reduction process, with possible strategies to check for their occurrence, is given in Sect. 3. A strategy for differential data reduction is outlined in Sect. 4. Finally, Sect. 5 contains the conclusions.

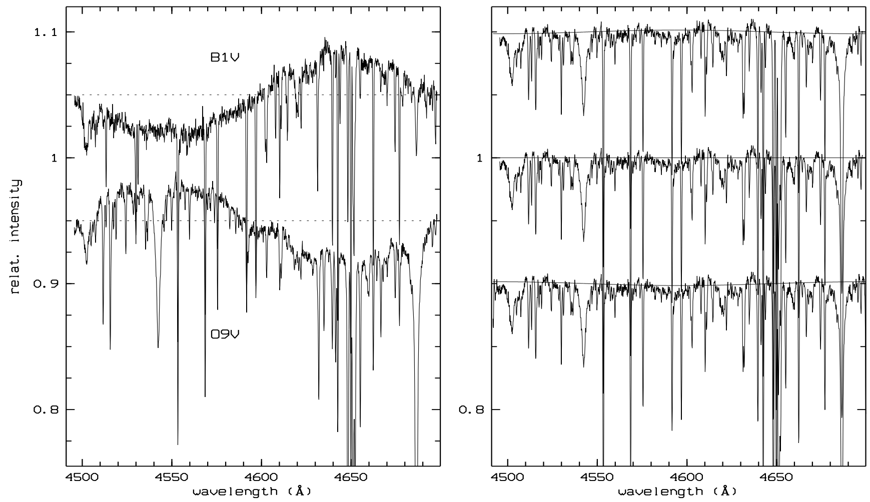

Figure 1. Two early-type spectra are deformed by an additive sine term with semi-amplitude 0.03 (left panel). The Doppler-shifted combined spectra (right panel; upper: B1V star shifted by 130 $\mathrm{km\,s^{-1}}$and O9V star by -80 km/s; middle: no shifts; lower: shifts as in 'upper', but in opposite direction) show a strongly reduced bending of the continuum. Full lines indicate the combination of the shifted sine curves.

2. Systematic noise in component spectra

A relevant question is whether small systematic errors in the input spectra remain small in the output component spectra. In order to show that this is not necessarily the case, it suffices to show that the combination of intrinsic spectra of two components, to which large systematic errors are added, can result in observed composite spectra with small systematic errors, independent of the applied Doppler-shifts. Such an example is easily constructed when combining the spectra with time-independent fractional light contributions ℓ_1 and ℓ_2 ($\ell_1 + \ell_2 = 1$). Besides the mathematical indeterminacy that occurs in this case of constant light (Hadrava 1995; Ilijić et al. 2004), it is easy to produce quasi-unbiased composite spectra when the Doppler-shifts $\frac{\lambda v_i}{c}$ are small with respect to the total length L of the disentangled spectral region. As a simple example, consider two intrinsic spectra to which sinusoidal disturbances are added with semi-amplitudes $A_{1,2}$ inversely proportional to $\ell_{1,2}$ and in antiphase with each other, such that $\ell_1 A_1 = -\ell_2 A_2 = A$, and with period L. Under zero RV-shifts the two disturbances cancel at all wavelengths in the composite spectrum, while under non-zero RV-shifts a sinusodial disturbance builds up. At the maximal RV semi-amplitudes $K_{1,2}$, the size of the disturbance in the composite spectrum is (with L and $K_{1,2}$ in the same units)

$$\frac{A_{\rm obs}}{A} = 2\,\sin\left(2\pi\,\frac{K_1+K_2}{2L}\right) \quad (1)$$

Eq. 1 expresses that $A_{\rm obs}$ is an order of magnitude smaller than A when $L \simeq 126\,\frac{K_1+K_2}{2}$, e.g. at H_β when L (Å) $\simeq K_1 + K_2$ ($\mathrm{km\,s^{-1}}$). Fig. 1 visualizes such a

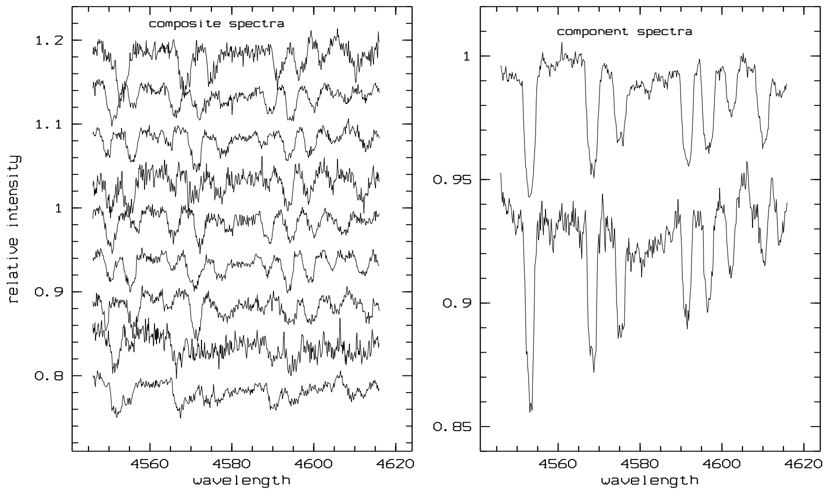

Figure 2. Extract of observed spectra of V578 Mon (left panel, spectra shifted in steps of 0.05 for clarity) and the disentangled component spectra of the early-B type components after normalisation to their intrinsic continua (right panel, spectrum of fainter companion shifted down by 0.05 for clarity). Note the spurious broad feature centered near 4580 Å, especially in the spectrum of the fainter companion (see text).

case. Reversing the argument, it is thus plausible that large undulations in the disentangled spectra may result from composite spectra with small undulations which correlate with orbital phase. Due to the relative light factors ($\ell_{1,2}$) the undulation will be more pronounced in the intrinsic spectrum of the fainter component. Is such a correlation with orbital phase likely to occur in practice? Yes: since the line blending varies with the Doppler shifts, the continuum windows in the composite spectra, and hence also normalisation errors, correlate with orbital phase. A somewhat similar situation of correlation of normalisation errors in the case of single early-type stars (in that case with line width i.e. rotation velocity) is discussed by Vrancken et al. (1997). Another example of how bias in observed composite spectra is amplified into disentangled spectra is given in Fig. 2. A small part of the observed composite spectra of V578 Mon around 4580 Å is shown together with the disentangled component spectra. The Si III triplet and O II lines dominate this part of the spectrum. But a broader depression at 4580 Å is obviously present in the spectrum of the fainter component, and only marginally visible in the brighter component and in the composite spectra. This feature can be traced back to a bias introduced by an unrecognised, very weak diffuse interstellar band or a broad, weak detector blemish feature in the composite spectra (below the 1% level) which is amplified by the inverse of the fractional light contribution of each component. The bias in the spectrum of the fainter component is sufficiently important to require a correction to the continua of the composite spectra and an improved disentangling before attempting an abundance analysis (Pavlovski 2004), while the input spectra appeared well normalised. The disentangling technique is simply a sensitive tracer of bias in the input spectra.

3. Systematic noise in echelle spectra

Systematic errors in echelle spectra may result from an inadequate data reduction process in several ways:

- bias in the model describing the geometry of the data on the detector;
- systematic differences between the calibration and the science frames, in particular concerning the intensity modulation by the blaze function;
- bias in continuum placement

Bias in continuum placement may be partly of astrophysical origin, but can also be a consequence of inconsistent merging of spectral orders due to bias described in the first two items.

3.1. Bias in the extraction model

Data reduction techniques for echelle spectroscopy are largely based on heuristic models, rather than on basic physics (see Ballester & Rosa 1997 for the latter approach and its limitations). As a consequence, the parameters used in the reduction process are chosen quite subjectively. The requirements which the data model should fulfill to transform the two-dimensional intensity surface of each order to a one-dimensional function of wavelength without bias were recently discussed by Piskunov & Valenti (2002). They are more stringent when applying a weighted extraction as opposed to simply summing the electrons in the direction perpendicular to the echelle dispersion (the *spatial* direction). The spatial profile is used in weighted/optimal extraction and in masking radiation events and detector blemishes. Hensberge & David (2000) show how to compute the gain in signal-to-noise for a specific spatial profile used in an optimal extraction, and they conclude that a significant gain occurs only at very low S/N. Weighted extraction algorithms are devised for the case wherein random noise largely dominates bias. A biased spatial profile leads to a biased flux estimate. Bias occurs e.g. due to limited accuracy in background estimation or flat fielding, but is mostly due to imperfect alignment of the spatial profile with detector columns or rows, such that spatial and spectral information gets mixed. Imperfect alignment is easily recognised by inspecting the spatial profile through a strong, sharp spectral feature. The left and right wings of lines show then apparent spatial profiles which deviate in opposite sense from the true one. Only recently, Piskunov & Valenti (2002) proposed an algorithm handling the spatial/spectral decomposition needed in the latter case. Verschueren et al. (1997) pointed out how spatial/spectral mixing results in masking pixels with valid data and thereupon in unphysical asymmetries in strong, sharp lines. They also discussed how other sources of systematic noise can be revealed by the radiation-event detection algorithm. A comparison of an unweighted extraction with and without masking suffices to judge the need for further concern. Ideally, differences should identify only very sharp features. Note that masking detector blemishes together with radiation events on a frame-to-frame basis includes the risk only to detect blemishes in high S/N images (e.g. flat-fields) and not in low S/N ones (e.g. science frames) such that they remain in the flat-fielded spectra.

It is prudent to compare the result of a weighted extraction with an unweighted one. Systematic patterns in the ratio of both extractions indicate bias. Plotting the ratio of the extractions relative to the sub-pixel fraction of the position of the spectral order in the spatial direction reveals then whether the bias correlates with the discrete character of the data. This occurs in case of a biased spatial profile or in an unweighted extraction when the length of the extraction slit is inappropriate. In case of densely packed spectral orders there may not be an unbiased solution without investing in the background subtraction algorithm.

A discussion of the complexity of the scattered light background in echelle spectra is given in Howk & Sembach (2000). Already much earlier, attention was drawn to the fact that the flux level in-between the spectral orders may remain well above the true background level (see e.g. Gehren & Ponz 1986). Interpolating the background model from the level observed in the inter-order space is still common practice and leads to strong telluric or interstellar lines going through the zero-intensity level, and, when a bright object and the sky background were measured simultaneously in two fibers, to negative sky background. Such negative fluxes hint to a biased background estimate, but other more indirect consequences, such as a biased spatial profile, may turn out worse in the end.

Note that it is important to check the bias in the extracted spectra at the level of the random noise or better. In the case of high S/N spectra, a visual check on the scale at which spectra are usually shown is inadequate.

3.2. Bias due to the intensity calibration

In order to calibrate the spectra in wavelength and to remove patterns introduced by the instrument and the detector ('flat fielding' in a somewhat extended sense) calibration lamps are often used. This may imply a different light path than for the science data, a different illumination of slit or fiber and, especially when aiming for a flat response over a large wavelength range, the use of filters. Experience shows that the low-frequency intensity modulation in calibration frames, and the time dependence of that modulation, may differ from the one in science frames. Especially a difference in the shape or position of the blaze function, or different vignetting, is transferred in low-frequency bias in the normalised spectral orders when using flat-fields to remove the modulation by the blaze function. Fig. 3 summarizes the continuous change of the position of the blaze function along the spectral order during a specific observing run. In that case, this change correlated strongly with the much smaller, but easier to measure, change in the projected position of the spectral orders on the detector, as measured in the spatial direction.

The ratio of extracted single spectral orders for identical exposures during an observing run (same science object or intercomparison of flat-fields) shows whether any time dependence is present, whether it is restricted to the calibration unit and to which factor it may be related. In the case that the blaze function itself is time-dependent, the introduced bias depends on the spectral order because the width of the blaze function changes proportional to wavelength. In the case of time-dependent vignetting, spectral orders are generally affected in a totally different way (see e.g. Fig. 4). When only calibration unit

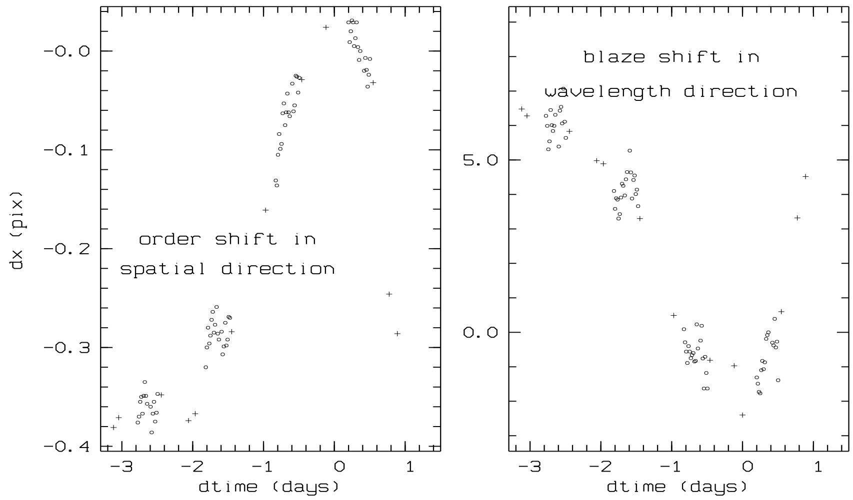

Figure 3. Correlation between the change of the spatial position of the spectral orders with time (left) and the change of the relative position of the apparent blaze function along the order (right). Data (stellar: o ; flat-field: +) from the FEROS spectrograph at ESO, 2002.

images are affected by a source of bias, dome flat-fields are useful to remove the unwanted low-frequency bias.

3.3. Order merging and continuum placement

When the intensity modulation by the blaze function is removed from the spectral orders, it is not uncommon that the intensity at the same wavelength, but in different spectral orders, differs significantly. Suzuki et al. (2003) demonstrate strong inconsistencies ($\simeq$ 10%) from HIRES on the Keck I telescope, while Erspamer & North (2002) show smaller inconsistencies in their Fig. 2. Straightforward merging of spectral orders would then result in a stepwise biased continuum.

It is mandatory to correct or avoid all low-frequency patterns before merging the spectral orders. Preferentially, such patterns should be corrected separately for science and calibration spectra in case they are different in both types of frames. This is not always feasible. Since the worst problems often occur at the edges of the orders, bias can be partly avoided by taking advantage of the overlap of subsequent spectral orders. When the intensity at some wavelengths is biased in one order, but not in the neighbouring one, information should not be combined (as one would do to gain S/N in case random noise dominates), but the edge of the affected order should be excluded. A modification of the wavelength range accepted for each spectral order (making the criterion more severe than in the reduction pipeline) has e.g. offered a viable solution for several observing runs which the author performed with the FEROS spectrograph at ESO. One should take care that affected edges of spectral orders have not influenced the estimates of the free parameters determined in the previous reduction steps, essentially by masking the concerned part of the detector. Another option is to model the time dependence in the ratio of extracted flat-field spectra

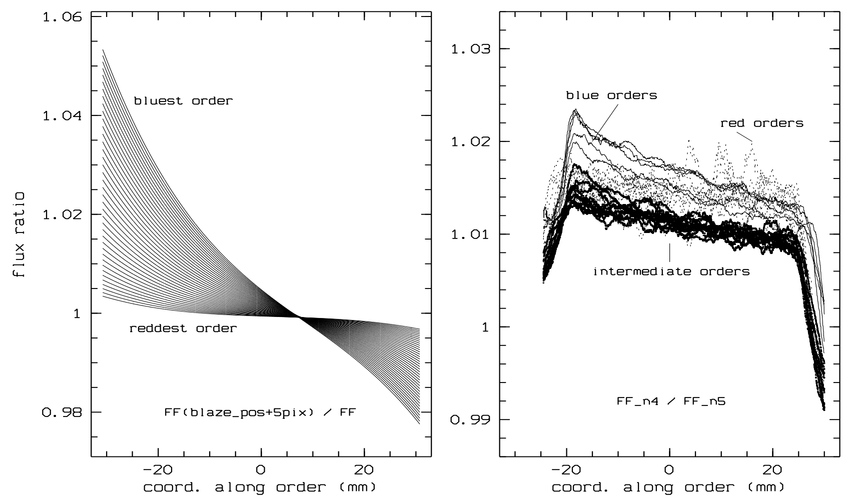

Figure 4. The flux ratio of extracted spectral orders in different flat-field exposures. The left panel shows a fitted model for identical blaze profiles shifted along the order by only 5 pixels in a 4096 pix long order. The narrower blue orders show a more pronounced effect. The right panel shows the observed ratio in a case of time-dependent vignetting at the edges of the orders (FEROS spectrograph at ESO, 2003). The effect does not correlate with the width of the spectral orders.

(and extracted science spectra, if needed), such that the remaining bias will be identical in all merged spectra. Such correction functions (Fig. 5) are usually well-behaved and vary smoothly from one spectral order to the next, which offers robustness that is lost when performing corrections on merged spectra.

When merging the spectral orders, the data are rebinned usually to equal steps in wavelength. Rebinning introduces correlation of noise between subsequent data points. Rebinning only once, from detector pixels to the coordinate which will be used in the analysis of the data, and conserving as closely as possible the original resolution results in lower correlations. It is fortunate that in echelle spectroscopy the original resolution corresponds much better to equal steps in velocity – the coordinate needed in the disentangling algorithms – than to equal steps in wavelength. Therefore, spectra should be immediately rebinned from the detector pixels to equal steps in the logarithm of the wavelength.

4. Differential data reduction

Time-dependent factors add complexity to the reduction of echelle data. In general the changes within one observing run require only minor alterations in the values of the free parameters defining the data reduction model on an absolute level. There is even no need to have all these free parameters when describing the time-dependent factors on a differential level. Differential corrections (e.g. to the wavelength scale, to the spatial position of the spectral orders, to temporal variations of low-frequency intensity modulations) require much less parameters, which leads to increased robustness. The choice of the minimum

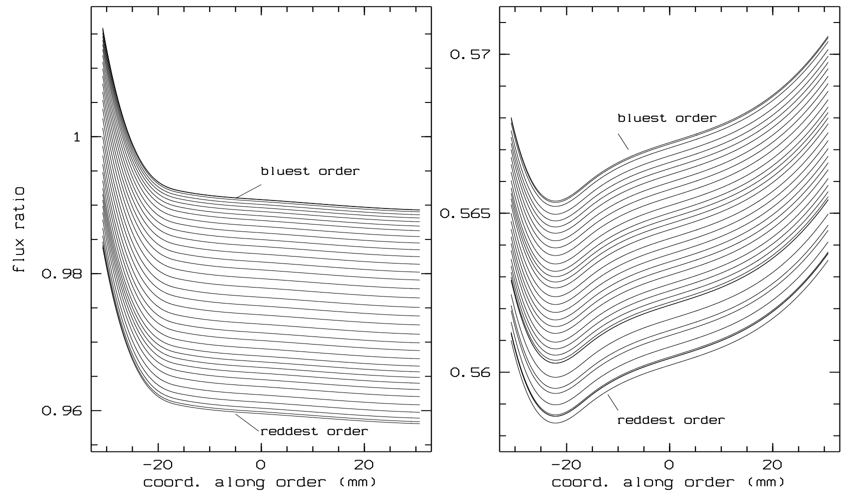

Figure 5. Models for the ratio of scientific exposures of the same star (FEROS spectrograph, 2002). The left panel refers to exposures obtained one shortly after the other. Note in both panels the sharper gradient at the start of each order, pointing to time-variable vignetting.

number of free parameters in a specific differential data reduction step is derived from a map of the difference in the relevant measurement (e.g. the position of a wavelength in an order) over the detector. An additional gain in precision is obtained from the fact that differential measurements are less sensitive to systematic effects than an absolute measurement. The automated measurement of the basic positional parameters in a differential way by the quality control team of a specific echelle spectrograph would provide a useful data base to identify the origin of the positional changes and to introduce more physics in the data reduction model. A specific analysis for the case of the FEROS spectrograph at ESO, including the description of a differential data reduction procedure, is available at http://www.ls.eso.org/lasilla/sciops/2p2/E1p5M/FEROS/Reports. Verschueren et al. (1997) already commented on the use of differential wavelength calibrations.

5. Conclusions

Systematic noise in observed composite spectra can propagate to the disentangled intrinsic component spectra with increased amplitude, contrary to the propagation of random noise.

Systematic noise in the composite spectra is often due to limitations in the data reduction procedure. The amplification of systematic noise by spectral disentangling makes the technique a sensitive tracer of the quality of the data reduction.

There is a need for continuous control of the stability of echelle spectrographs at a better level than presently performed if one wants to push spectral disentangling to its limits. Systematic noise in the extracted spectra should be identified and, ideally, eliminated before removing the intensity modulation due to the blaze function and before merging the spectral orders.

A differential data reduction procedure allows one to reduce drastically the number of free parameters and to obtain more consistently normalised sets of spectra for a specific object.

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