EXTRACTING STELLAR PARAMETERS FROM OBSERVED SPECTRA: THE ROLE OF CROSS-CORRELATION AND MINIMUM DISTANCE METHODS

Tomaž Zwitter[1]**, Ulisse Munari**[2]**, Arnaud Siebert**[3]

[1]University of Ljubljana, Dept. of Physics, Ljubljana, Slovenia
[2]National Institute of Astronomy, Padua Astronomical Observatory in Asiago, Italy
[3]Steward Observatory, Tucson, AZ, USA

ABSTRACT

One may consider cross-correlation routines applied to stellar spectra as a way to determine not only the radial velocities but also to assess the properties of stellar atmospheres. We show that this is not the case. A high value of the cross-correlation coefficient between the observed and a template spectrum does not mean that the template corresponds to correct values of stellar temperature, gravity or metallicity. Cross-correlation operates in normalized space, so it is not sensitive to scaling or shifting of stellar flux. It is argued that cross-correlation is useful to efficiently determine the velocity shift between the observed and the template spectrum. But minimal distance methods need to be used to determine which template gives the best match to the observed spectrum, and so derive values of physical parameters. To illustrate the point we use data from the RAVE project which are being obtained at very similar spectral resolution and wavelength domain as will be the case for Gaia's RVS.

Key words: Stars: fundamental parameters; Methods: data analysis.

1. INTRODUCTION

In the attempt to extract values of physical parameters from stellar spectra one first tries to determine the value of radial velocity. If the spectra have a wide wavelength coverage, like in the case of ELODIE spectra, it can be assumed that a fixed spectral mask gives radial velocities with sufficient accuracy (Katz et al. 1998). Analysis of Gaia radial velocity spectrometer (RVS) data will profit from quite accurate knowledge of stellar parameters obtained from on-board photometric observations. So all simulations of Gaia radial velocity determination assumed that the choice of a proper template is given by complimentary photometric data (Katz et al. 2004, Munari et al. 2003, Zwitter 2002). Alternatively, it was assumed while assessing the capabilities of Gaia spectra to independently determine the values of stellar parameters, that the radial velocity is *a priori* known (ESA 2000; Thévenin et al. 2003; Katz et al. 2004). Note that these approaches are relevant at the end of the Gaia mission, but at the start of the mission virtually nothing will be known about the values of stellar parameters, so that one would not know which kind of template to use for a radial velocity determination. Also, the wavelength coverage of Gaia spectra is much smaller than that of a typical Echelle (ELODIE) type spectrum. So we attempt here to determine *both* the best radial velocity and the values of parameters of the stellar atmosphere simultaneously. Data from the RAVE experiment, which are very similar in both wavelength coverage and resolution to those of Gaia's RVS, will be used to illustrate the point. Note that since virtually nothing is known about the RAVE targets it is obvious to use such an approach.

2. OBSERVED SPECTRA

RAVE (RAdial Velocity Experiment) project (Steinmetz 2003, Munari et al. 2005) is an ambitious international collaboration aimed at conducting an all-sky spectroscopic survey of Galactic stars. The participating countries are Australia, Canada, France, Germany, Italy, Japan, Netherlands, Slovenia, Switzerland, UK, and USA. The spectra allow us to measure radial velocities as well as metallicites and other stellar parameters for a large number of stars using the 1.2m UK Schmidt telescope at the Anglo-Australian Observatory. Data collection for this project started in April 2003 with more than 40 000 spectra observed to date. Spectral resolving power and wavelength range (8413–8746 Å) are very similar to those of the Gaia Radial Velocity Spectrograph.

3. LIBRARY OF SYNTHETIC SPECTRA

Observed or synthetic spectra can be used for classification. The advantage of the former is that they are 'real', so avoiding any simplifying assumptions used in synthetic spectra calculation (Munari et al. 2001). The latter have the advantage of a more uniform coverage of the parameter space. At present we are using a subset of a

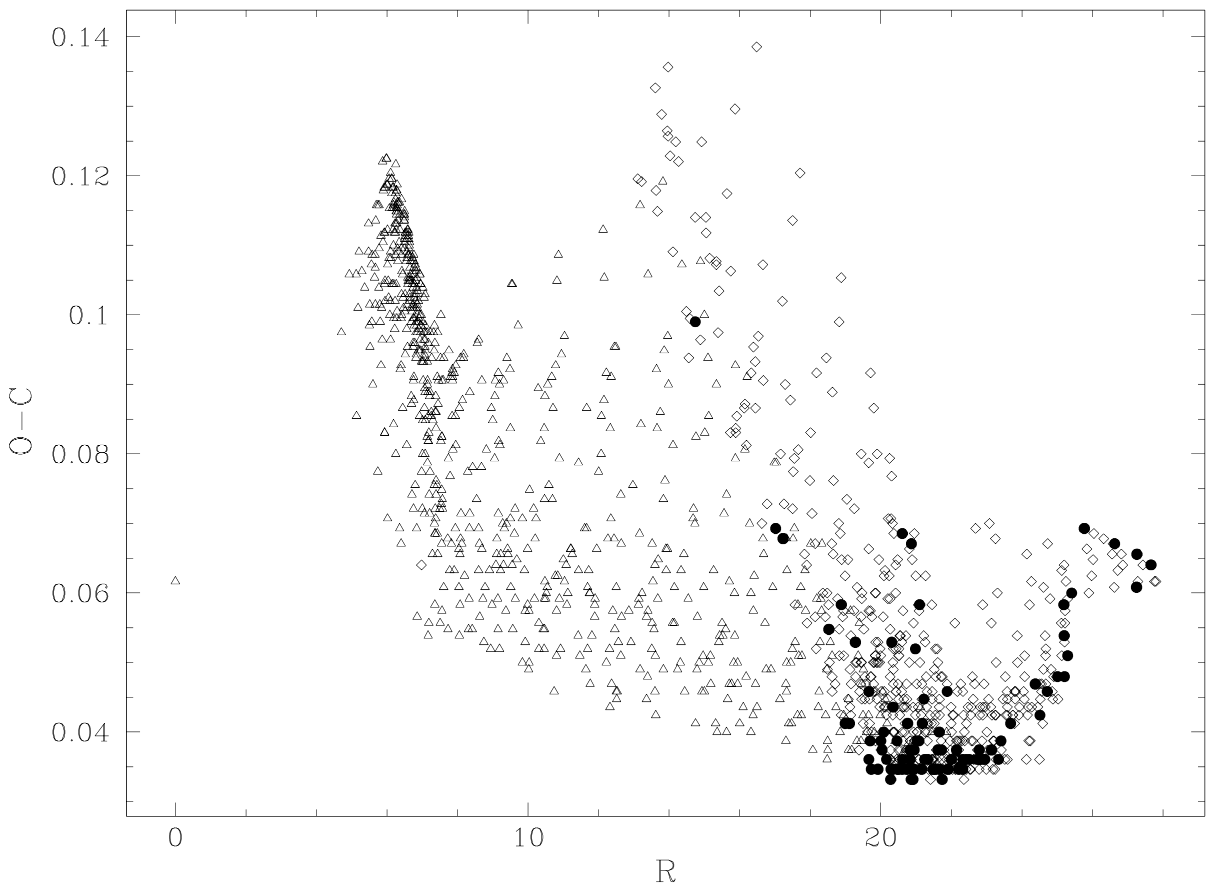

Figure 1. Fits of templates with the best value of correlation coefficient R are not necessarily those with the smallest value of the standard deviation (O–C) between the observed and template spectra. The later is given in units of continuum. Each point presents results of a cross-correlation and standard deviation for one template from the data base. Symbol type marks the difference between the calculated value of radial velocity for a given template and the one for a minimal O–C template: less than 0.2 km s^{-1} (•), up to 2 km s^{-1} (◇), or more (△).

synthetic library of nearly 60 000 spectra with suitable resolving power (Zwitter et al. 2004) which were calculated from the latest generation of Kurucz models. The grid is characterized by the following ranges of stellar parameters: 3500 K $\leq$ $T_{\rm eff}$ $\leq$47 500 K, 0.0 $\leq \log g \leq$5.0, $-3.0 \leq$ [M/H] $\leq$ +0.5, 0 $\leq$ $V_{\rm rot}$ $\leq$500 km s^{-1}, ξ =2 km s^{-1}.

4. USING CORRELATION ROUTINES ONLY

Correlation routines, like the IRAF's rvsao package (Kurtz & Mink 1998) are a well established way to calculate radial velocity using a fixed stellar or galaxy spectrum template. Their figure of merit is based on the value of correlation coefficient R (Tonry & Davis 1979). But one should not conclude that the template spectrum with the highest value of R also gives the best fit to the observed spectrum. Figure 1 shows results of analysis of a single observed spectrum using a set of template spectra. The maximal value of the correlation coefficient R occurs at the 'stem' of area covering a caravel ship shape, though the minimum of $O - C$ occurs at its bottom. The reason is that the correlation is defined using normalized quantities. Therefore it is not sensitive to any kind of constant shift or spread (of the kind $x + a$ and $x \times a$ where a is a constant value or bias). This explains why it is only sensitive to high variations in the line profile and is not suitable for minimization.

We can also say that in cross-correlation one tries to find the best alignment of the lines, in a way irrespective of their depth. This is strictly valid for isolated single lines. The effective wavelength of a blend of nearby lines can shift sideways and so worsens the cross-correlation only with a large change of the temperature and gravity.

Figure 2 plots the observed spectrum which was used in Figure 1 and one of the templates from the library. The match is poor even though the template shown features the highest value of the correlation coefficient R among all templates in the library (the point is at the tip of the stem of the caravel shape in Figure 1). Cross-correlation alone is clearly not enough to find the template with the best match.

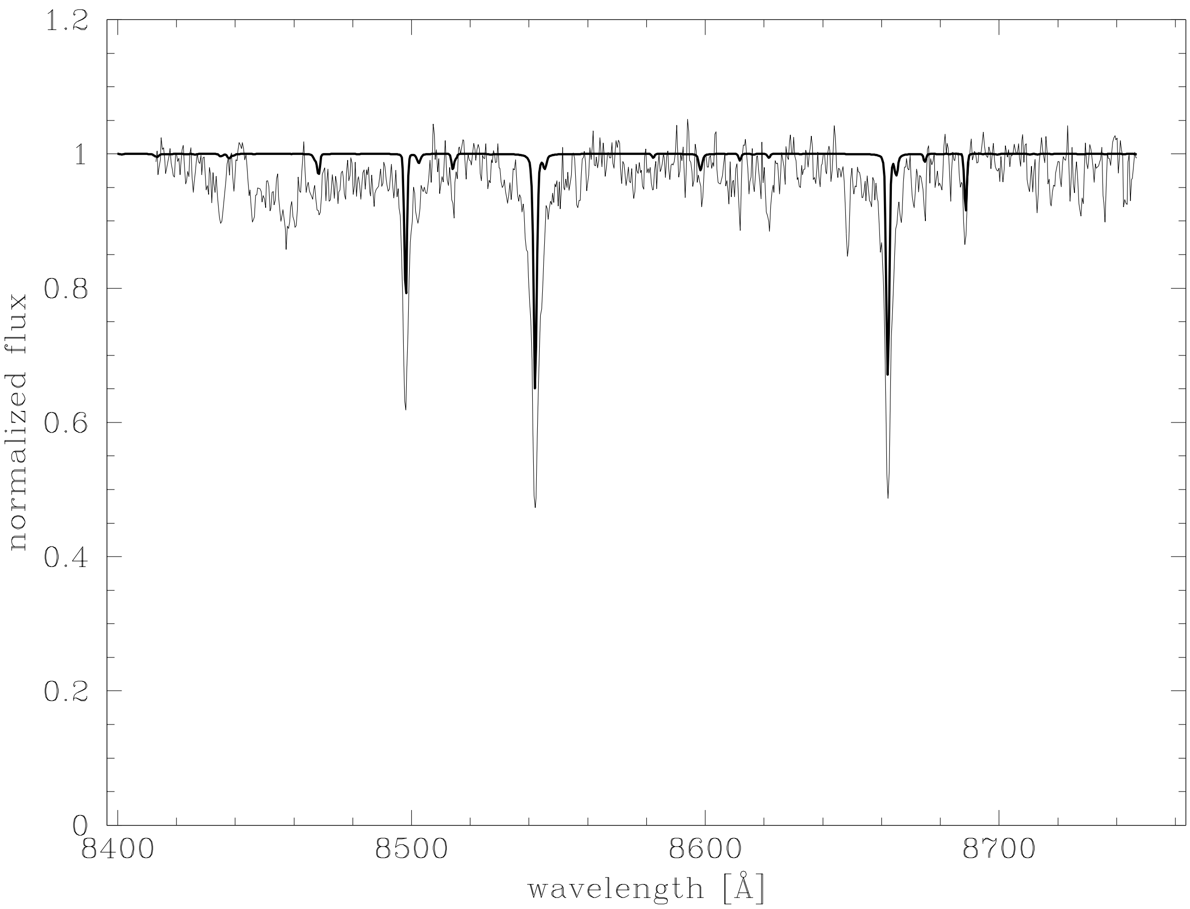

Figure 2. Match between the observed (thin-line) and template spectrum (thick-line) is poor, even though this is the template which yielded the highest value of the correlation coefficient R in Figure 1.

5. ADDING A MINIMAL DISTANCE METHOD

The situation can be improved by supplementing correlation analysis with a proper minimization scheme (Figure 3). The reason is that normalized squared distance is sensitive to line depth and shape as well as continuum level, and so to the values of stellar parameters.

In our case we first use a correlation routine to calculate the velocity shift between the observed spectrum and a template from the synthetic library. But the goodness of fit is not based on the value of the correlation coefficient R. Instead we calculate the standard deviation between the observed spectrum and the velocity-shifted template. The template which yields the smallest standard deviation is assumed to give a fair representation of parameters of the stellar atmosphere.

6. RELEVANCE OF RAVE, GAIA AND OTHER AUTOMATED CLASSIFICATION PROJECTS

Values of several stellar parameters are primarily based on spectral analysis. These include metallicity, abundances of individual elements and stellar rotation velocity. The values of effective temperature and surface gravity can also be derived, or in the case of Gaia checked, by spectral analysis. Both Gaia and RAVE projects will provide too many spectra to be analyzed by hand. Automated procedures, such as the one proposed here, yield useful results. Any other information available, in the case of Gaia these would be results of photometric and astrometric observations, can be seen as an additional constraint on the relevant range of stellar templates to be considered for a given star. If an acceptable match could not be found despite a high S/N of the observed spectrum, this implies that any kind of peculiarity is present in the observed object, or that the observed star is a double lined spectroscopic binary.

7. CONCLUSION

Cross correlation is sensitive to position of the lines and so radial velocity. It is however not sensitive to line depth, so it is not to be used to determine the values of stellar atmosphere parameters unless blends of nearby lines are driving the correlation. The situation gets worse with low S/N spectra and when sharp lines (e.g., Ca II

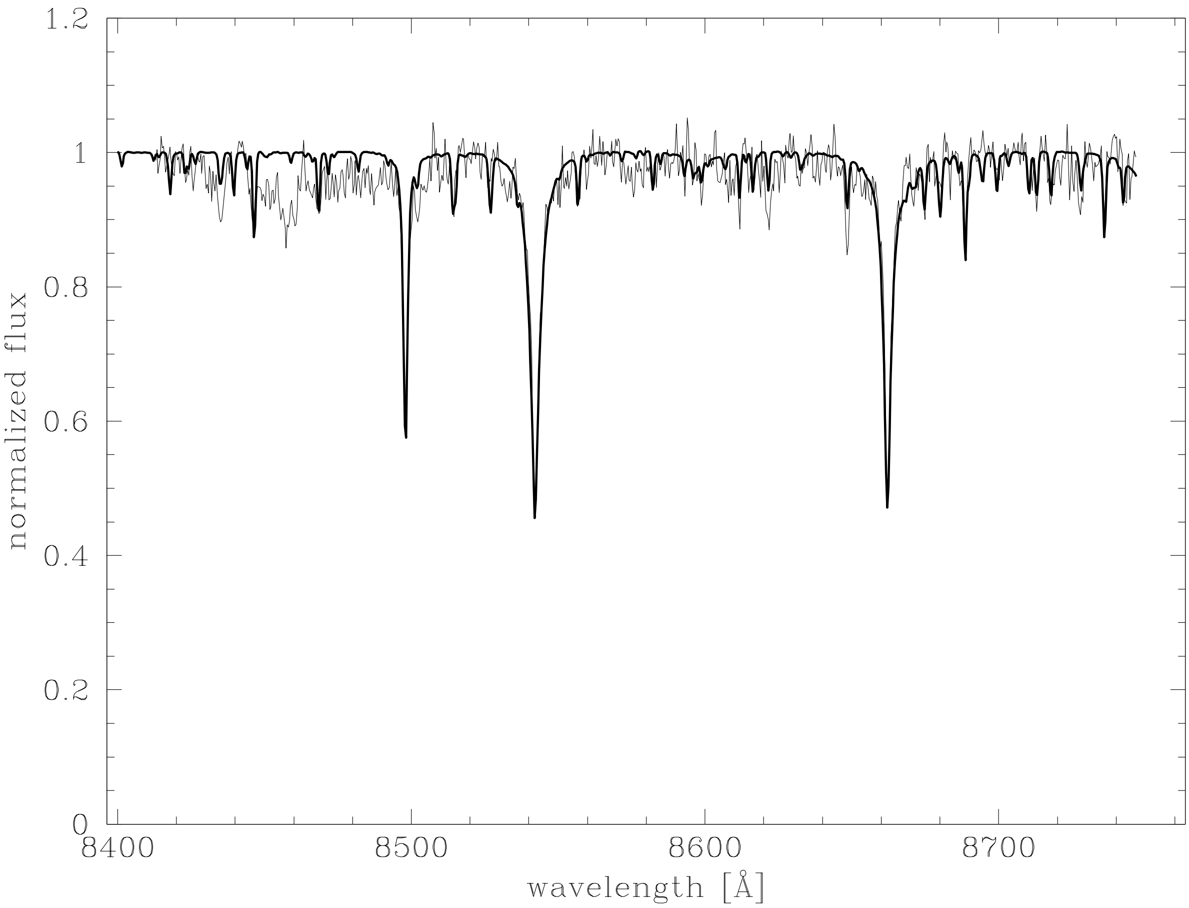

Figure 3. The match between the observed (thin-line) and template spectrum (thick-line) is much better when a suitable minimization scheme is used as a figure of merit. The template and observed spectrum correspond to the lowest $O-C$ point in Figure 1.

IR triplet) are present. By adding a suitable minimum distance scheme which is sensitive to equivalent widths (Thévenin & Foy 1983) the values of both radial velocity and stellar parameters like temperature, gravity, metallicity and rotation velocity can be determined reliably.

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