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Update on crowding of stellar spectra in the GAIA spectro instrument

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Abstract

To the best of my knowledge all studies of crowding of stellar spectra in the Spectro instrument calculated the overlappers on a single transit and then simply multiplied the result 100-times to get the whole mission background. This is wrong as overlappers are different on each transit. As a result the obtained background spectra were too jumpy because the same background star unrealistically occurred on each transit and at the same position.

Here we improve on this issue by generating a new realization of background for each transit. The resulting background spectra are smoother and so easier to model and subtract. Sample spectra are generated for four star densities: 1 000 (i.e. halo), 6 000 (disc), 20 000 and 40 000 (extreme densities/bulge) $V < 17$ stars per square degree. We briefly discuss some basic summation strategies to obtain an end-of-the mission spectrum of a given star. The need to develop a full 2-D spectro simulator is emphasized.

1 Introduction

Spectro instrument is a slitless spectrograph, so some spectra overlap is unavoidable. Basic treatment including formulae describing probability of overlaps is outlined in Zwitter (2003, in GAIA Spectroscopy, Science and Technology , ASP Conf. Ser., U.Munari (ed.), 298, 493). M. Cropper presented progressively improved 2-D realizations of the background and analyzed the resulting RV accuracy in the last four RVS workshops. D. Katz generated several background spectra to be used for a double-blind test in the near future. To the best of my knowledge all this work (except David's) built on one important simplifying assumption: the background was calculated for one transit, and then multiplied 100-times to obtain an end-of-the-mission spectrum. Everybody understood that this is unrealistic as the overlappers are different on each transit. But the assumption was kept due to a limited computing power and a much increased complexity of the analysis if things are done properly.

Here we generate more realistic backgrounds for several star densities. We show the result is much smoother than claimed before, therefore any measurement of RVs or other stellar parameters can be less concerned with the presence of spectral lines from background stars. Consequently also the analysis software will have to go through less iterations to obtain an acceptable convergence.

I would like to mention that the motivation for this note came from a discussion with Mark Wilkinson while walking to the conference dinner at the recent RVS workshop in Nice. He explained to me the potential importance of analysis of the very dense regions, so examples of very crowded spectra are included in this note. I do leave it to him and writers of the 2nd paper on the Spectro instrument to decide on the limits of still useful star densities, but data are here.

This note does not improve significantly on published modeling of the obtained background spectra. Assumptions very similar to Zwitter (2003) are used to obtain a recovered spectrum. The result is however encouraging as smoother background spectra are clearly easier to treat than the previous jumpy ones.

2 Generation of background spectra

A background spectrum is generated using the following assumptions:

1. Spectrograph has a resolving power of 11 500, sampled at 0.375 \AA per pixel.
2. The spectral tracing is always 2-pixels (2.9 arcsec) wide.
3. No profile fitting is taken into account: the spectra either overlap in the direction perpendicular to dispersion or they do not overlap at all. This is a conservative assumption. Partial overlaps will result in more overlaps but with less of the signal per overlap. So realistic spectra will be even smoother than derived here. A proper treatment of this issue will require decision on data transfer

rate (do we sum across dispersion signal before transferring it to the ground?) and development of a complete 2-D simulator.

4. Stellar field is represented by a single parameter (star density), positions of stars are random for each transit. This assumption is quite realistic for general fields of the halo, disc or bulge, but analysis of dense star clusters of dimension smaller than the spectro field of view or of compact visual pairs would obtain less optimistic results than derived here.
5. Magnitude distribution follows a simple formula: $dn/dm \propto 2.3^{m-0.05(m-15)^2}$ (Zwitter & Henden 2003, in GAIA Spectroscopy, Science and Technology, ASP Conf. Ser., U.Munari (ed.), 298, 489). The quadratic term dumps the distribution at faint magnitudes. This form works in the general field but may be of limited use in fields with significant reddening or for the case of reach distributions of faint stars (bulge).
6. All background stars have a spectrum of a K1 V star ($T=5000\text{K}$, $\log g = 4.5$, $[M/H] = 0.0$, microturbulence = 2 km s^{-1} , $v \sin i = 2 \text{ km s}^{-1}$). Such overlappers will be most common, but other spectral types will add to the mix. Most other metallicities and spectral types feature spectra with less intense spectral lines. So our assumption is a simplification but moderately so.
7. Stellar positions are accurately known. This is certainly true: an error of 1 miliarcsec in the dispersion direction, i.e. a very crude astrometric position by GAIA standards, corresponds to a shift of just 0.001 pixel or 13 m s^{-1} , i.e. a negligible RV error.
8. Stellar magnitudes (flux level) are accurately known. Very small photometric errors as well as simultaneous star mapper measurements justify this assumption. Accurate flux levels imply also an accurate knowledge of the transmission of the filter which limits the wavelength domain of the spectro instrument. For the purpose of this note we use a \cos^2 filter within 30 \AA of the spectral edges.

3 Background spectra recovery

This note uses limited information on positions, magnitudes, spectral classification and velocity to model the background signal. The aim is to illustrate how accurately one can guess the background without iterating the solution too much.

The following information was used to recover the background:

1. Accurate knowledge of positions of all background stars (see item 7 above).
2. Accurate knowledge of magnitudes of background stars (see item 8 above).
3. Limited knowledge of spectral type and metallicity of each background star. For the purpose of this note it was assumed that the background star has the parameters: $T=5250\text{K}$, $\log g = 4.0$, $[M/H] = -0.5$, microturbulence = 2 km s^{-1} , $v \sin i = 10 \text{ km s}^{-1}$. Comparing this with item 6 above shows that we assumed an error of 250 K in temperature, 0.5 dex in metallicity and gravity and 8 km s^{-1} in rotational velocity. This numbers are conservative, roughly they correspond to middle mission solution for the background stars.
4. The radial velocity of the background stars is known only at limited accuracy. The RV error was assumed to be $2 \times 2.51^{V-14} \text{ km s}^{-1}$. So the error was 2 km s^{-1} at $V = 14$ and 20 km s^{-1} at $V = 16.5$. These error values are realistic but I feel exact numbers do not matter much: an error of 20 km s^{-1} corresponds to a shift of 0.6 \AA . If we compare it to a typical width of 10 \AA for the prominent spectral lines we see that the background lines get subtracted quite well even if the radial velocity errors are quite large.

Figure 1 shows spectra used to generate and to recover the background signal.

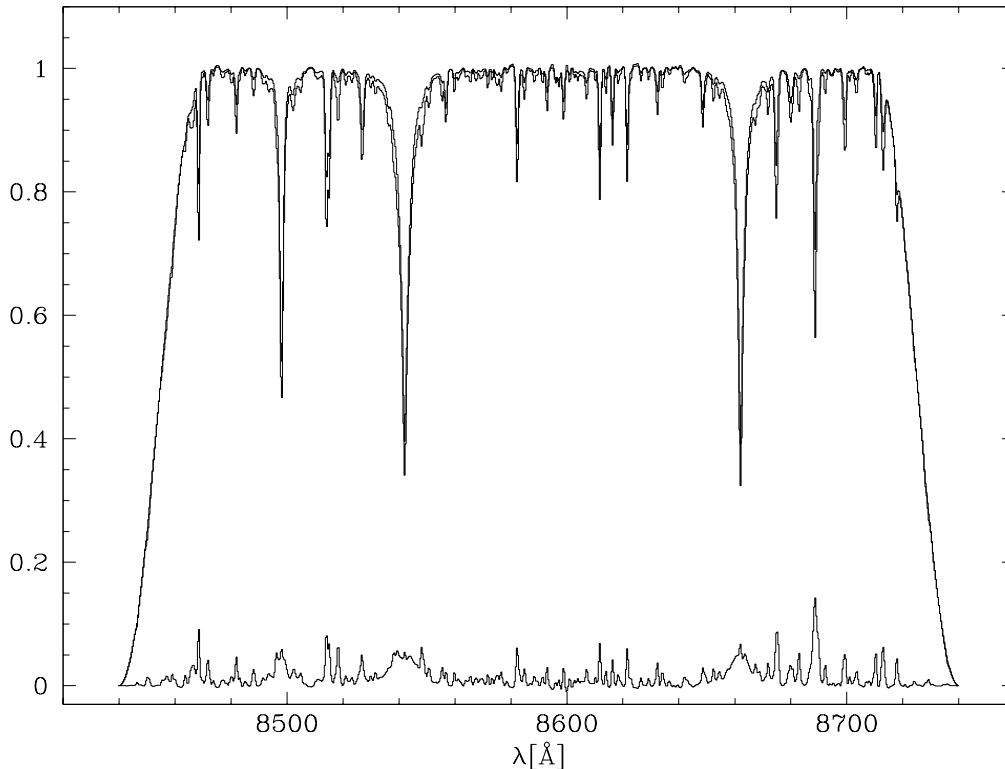


Figure 1.

The spectrum used to generate the background ($T=5000\text{K}$, $\log g = 4.5$, $[M/H] = 0.0$, microturbulence = 2 km s^{-1} , $v \sin i = 2 \text{ km s}^{-1}$), the one used to model (recover) it ($T=5250\text{K}$, $\log g = 4.0$, $[M/H] = -0.5$, microturbulence = 2 km s^{-1} , $v \sin i = 10 \text{ km s}^{-1}$), and their difference (hotter minus cooler). All spectra were trimmed at their edges with an assumed \cos^2 filter transmission function.

4 Examples of background spectra

Figures 2 and 3 show examples of backgrounds accumulated over the whole mission for four different stellar densities. Note that spectral lines from individual spectra are present in the summed signal, but they are diluted quite a bit due to the fact that overlappers change from transit to transit. Also the result of approximate modeling of the background signal gives satisfactory results.

5 How to sum spectra from individual transits

Figures 2 and 3 show a straight sum of all overlapping stars accumulated over the whole mission. It is obvious however that a few of the brightest overlapping stars contribute a significant fraction of the whole-mission background. They are also responsible for most of the spectral lines seen in the summed background.

One should obviously ask if omission of a few transits when our object spectrum suffers from a very bad overlap by a bright nearby star can improve the situation. It is obvious that we lose some of the object's signal, but the resulting whole-mission background will also be lower, smoother and so easier to model and subtract.

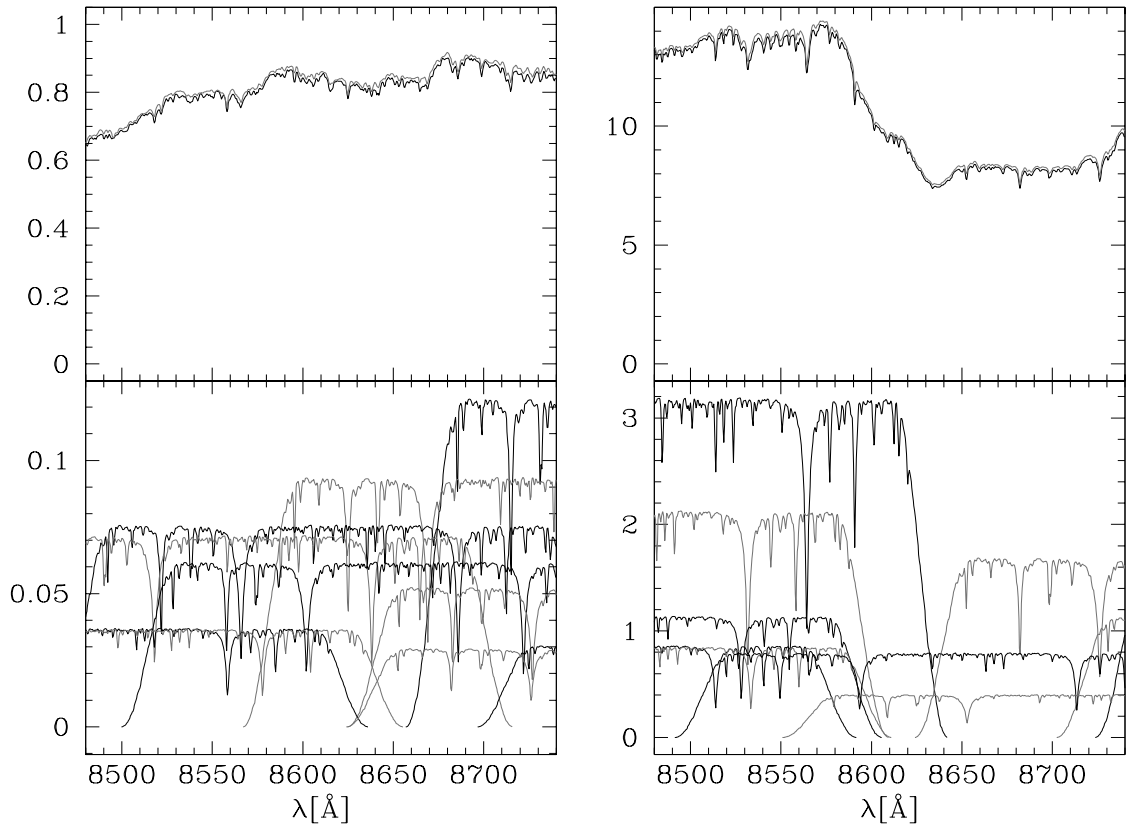


Figure 2.
 Crowding of stellar spectra in the focal plane of the slitless spectrograph results in spectral overlaps. The left panels depict situation typical for the Galactic halo (~ 1000 stars/deg² with $V < 17$), the right ones are for a more crowded region near the Galactic plane (~ 6000 stars/deg² with $V < 17$). Top panels show the background accumulated over the whole mission. The true background is plotted in black and the one recovered from the astrometric and photometric information from other instruments aboard GAIA in gray. Bottom panels show contributions of the 10 strongest overlapping stars. Ordinates are fluxes in units of flux from a $V = 17$ K1 V star integrated over the whole mission.

Figure 4 gives an example of such a strategy. Any transit with a (partially) overlapping star brighter than $V = 14$ was omitted from the whole-mission background sum. So the resulting background is less jumpy, shows less spectral lines and has (for the case of galactic disk) significantly lower intensity. The realization of background in Figures 2 and 4 is not the same so specific overlappers do not occur in the same position.

Such a crude strategy clearly lowers also the integrated signal from the observed object. An imposed heuristic $V = 14$ limit meant that 3% of all transits were thrown away for the case of stellar densities typical in the Galactic halo. In denser regions the fraction of bright transits increases: in the disc it raises to ~ 13 %. One should obviously decide for an optimal cut-off magnitude depending on stellar density. For example an $V = 14$ limit would throw away most of the transits (and so the signal) at extreme stellar densities (Fig. 3). But it is obvious that throwing away the ~ 10 transits where the 10 strongest overlappers occurred would roughly half the background in both cases from Figure 3. Losing 10% of the signal from the star we analyze and cutting its background in half is not a bad result if the

star is so faint that the background contribution is critical.

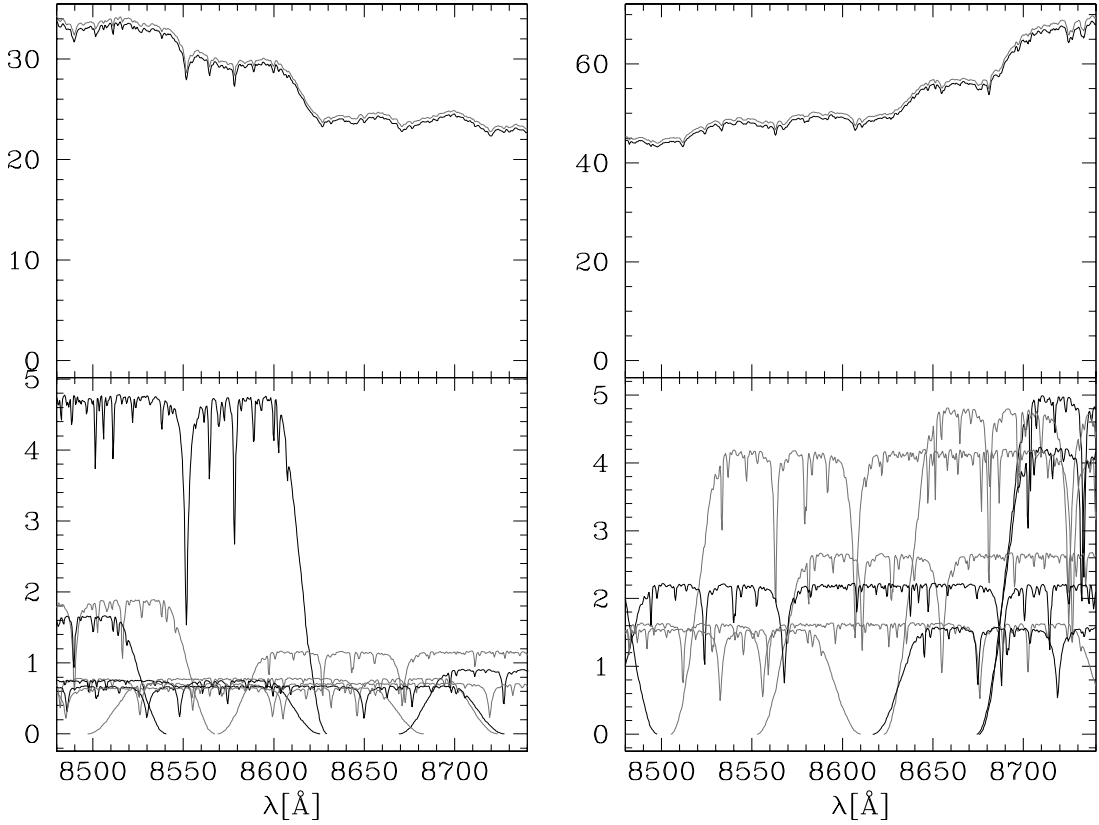


Figure 3.
Same as Fig. 2 but for regions of extreme stellar density: 20 000 (left panels) and 40 000 (right panels) $V < 17$ stars/deg².

6 Conclusions

We showed that the background signal is remarkably smooth and can be well modeled. It is obvious that a simple sum of all spectra obtained during the whole mission is not the best strategy. If our star is faint and resides in a region of high stellar density it is best to omit the transits with very bright overlapping stars from the final sum. A rough estimate shows that the background signal can be roughly halved if we omit some 10 most problematic transits out of 100 transits collected during the whole mission. This means that the resulting background from overlapping stars would be quite smooth. Its intensity would correspond roughly to the following values:

stellar density (stars brighter than $V = 17$ per square degree)	background level (in units of continuum flux from a $V = 17$ star)
1 000	0.8
6 000	5
20 000	15
40 000	25

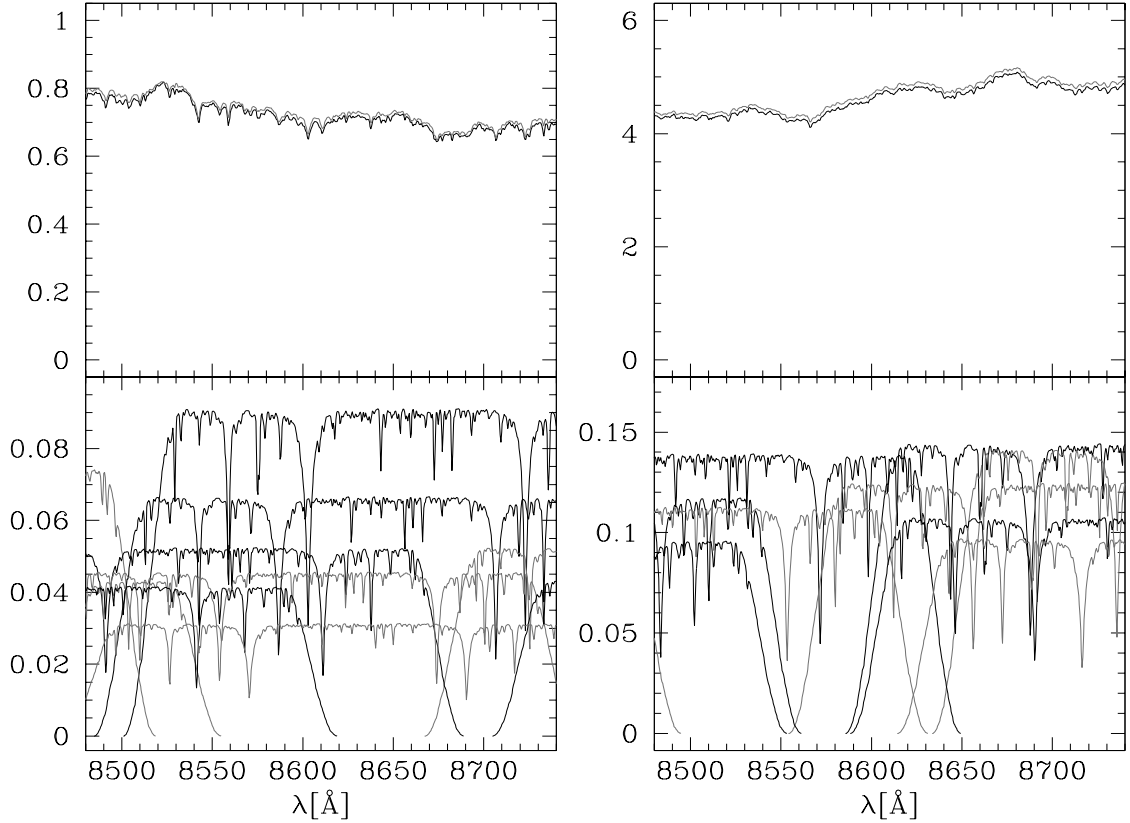


Figure 4.
 Same as Fig. 2, but now all transits with overlapping stars brighter than $V = 14$ were omitted from the whole-mission background sum. Such transits occurred in 3% of the cases (halo densities at left) and 13% of cases (disc densities at right). The resulting background is much smoother and of lower intensity while the loss of the signal is still acceptable.

Modeling of the background (gray lines in top panels of Figs. 2-4) yields satisfactory results. Note that the ordinate is in units of (whole mission) flux from a $V = 17$ star. GAIA will be obviously very much limited by small number of collected photons at these faint magnitudes. So concerns of some small errors in the background modeling seem less important.

It is obvious that the present note cut some corners:

- (i) the simulation is not 2-D;
- (ii) some spectra will suffer from large systematic errors, i.e. due to binarity, atmospheric activity etc;
- (iii) one should develop a refined strategy of how to treat transits with bright overlapping stars; throwing them away is clearly inferior even to using a simple weighting scheme.

Two things are however very obvious:

- the fact that the background is different on each transits makes the background spectra significantly smoother than claimed before and so easier to subtract;

- all summation and analysis strategies are part of the ground based software package, so they can be constantly improved and applied differently depending on the brightness of the star or the purpose of its analysis (just velocity or also its atmospheric parameters).

A complete 2-D simulator for the GAIA spectro instrument is clearly needed to address all these issues.

I believe the present note shows the overlapping stars can be handled very effectively. So the main conclusion is that the background decreases the results mainly by increasing the shot noise level of the spectra. In particular the background level due to overlapping stars roughly corresponds to the signal from a star with magnitude $V = 17.2$ (Galactic halo, $n = 1000$), $V = 15.2$ (Galactic disc, $n = 6000$), $V = 14$ ($n = 20\,000$), $V = 13.5$ ($n = 40\,000$). Note that these numbers are very crude estimates and could be easily improved by another 0.5 mag or even more using a better summation strategy. Anyway, stars with the above magnitudes would have their S/N ratio decreased by $\sim 40\%$ and the ones 1.2-mags fainter would have their S/N halved. So stellar background will not degrade results significantly for typical densities of the Galactic halo or disc, but will perhaps limit useful results to $V < 16$ for the very dense regions ($n \sim 20\,000$).