MSC performance on cycle 5 simulated data

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Abstract

This document describes the results of the first tests on the performance of MSC using simulated Cycle 5 spectra of binary stars.

Contents

1 Introduction

Using simulated Gaia spectra of binary stars we have estimated the precision of MSC algorithm in the prediction of the most significant parameters for these objects. The tests have been performed using data with and without extinction. In the case that extinction is not included in the spectra we have estimated the effective temperature, the luminosity and the gravity for both stars as well as their brightness ratio. For these set of spectra we have also tried to estimate the metallicity, but since the values of this parameter lay on a discrete grid, the performance is not representative and will not be presented in this report. Additionally, since the spectral library has been simulated only for a single value of the alpha elements abundance no tests have been performed for the estimation of this parameter. In the case of reddened spectra we extracted the values of A_0[1], the temperature of the primary star and the brightness ratio between the two stars. As a final step we have compared our results with the results given by GSP-phot for the same test set of spectra but with models trained with spectra of single stars. This was made in order to demonstrate that despite the fact of the two codes being almost the same, training on the appropriate set of data is very important. In the future we are planning to test various ways to improve and develop the MSC algorithm and this report will be the base line for our comparisons.

2 Software and data

For the results presented here we have used simulated BP/RP spectra of binary stars from Cycle 5 (GAIA-C8-DA-OAPD-RS-004). This data sample includes 100,000 spectra of binaries simulated for three different G magnitudes (15, 18.5 and 20 mag). For the sample corresponding to G magnitude 20 the spectra are only provided with artificial reddening (A_0 parameter in the range from 0 to 10 mag). For the other two values of magnitude the sample is produced both with and without reddening effects. In all the results presented below MSC models were trained using a subsample of 10,000 spectra while the remaining 90,000 were used to test their performance. In figure 1 we present the temperature and gravity of the primary and the secondary star as well as the distribution of the brightness ratio for all the binary stars in the library.

The version of MSC used here is 4.0, which was delivered in cycle 6. For a detail description of the MSC see the algorithm's cycle 6 STR (GAIA-C8-SP-MPIA-PAT-005). In this version, MSC is mainly a copy of GSP-phot but with the ability to estimate a larger number of parameters (i.e. the luminosity of the primary star, the brightness ratio between the two components and the parameters characterizing the secondary star). For that reason we also performed again a subset of the tests performed with the MSC using GSP-phot in order to check the impact of the choice of training set on the accuracy of the parameter estimation. GSP-phot was also trained with Cycle 5 simulated BP/RP spectra, but this time using the random grid of single stars instead of

[1] The A_0 and R_0 parameters presented in this report correspond to the parameters included in Cardelli's extinction law: $A_\lambda = A_0[a(\lambda) + b(\lambda)/R_0]$

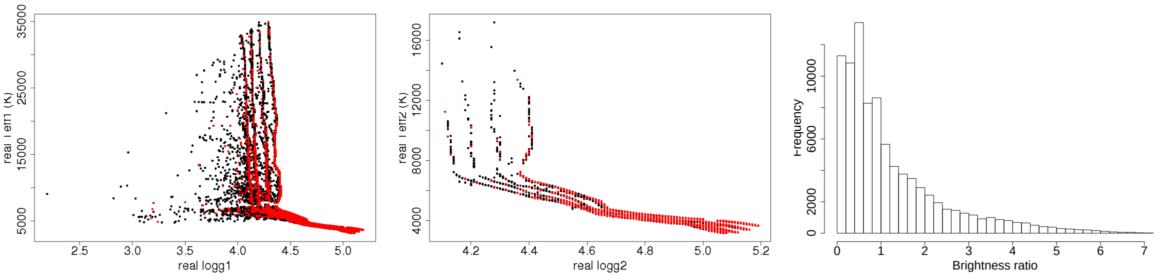

Figure 1: The Teff vs. logg for the primary (left) and the secondary star (middle) for the whole simulated library of binary stars. With red and black we present the sets that were used to train and test MSC respectively. Right: The distribution of the brightness ratio for all the binary stars in the library.

binaries, (GAIA-C8-DA-OAPD-RS-004). As a result only parameters for the primary star can be estimated by GSP-phot. The distribution of the effective temperature and gravity parameters for the single stars used to train the GSP-phot models can be seen in figure 2. The version of GSP-phot used for the tests performed here is 6.0 and delivered in cycle 6. For more details about GSP-phot please see its cycle 6 STR (GAIA-C8-SP-MPIA-CHL-002).

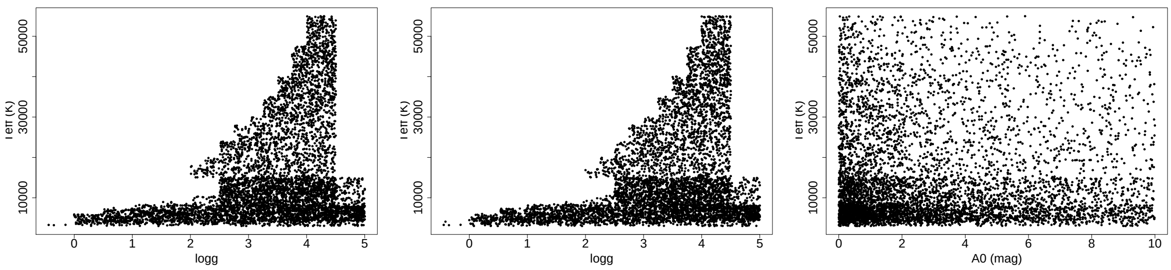

Figure 2: The Teff vs. logg for the stars used to train the GSP-phot models without (left) and with (middle) extinction effects. In the right plot the Teff vs. A_0 for the training set of stellar spectra with extinction is presented.

The results of GSP-phot on the estimation of binary stars APs are presented in section 5 of this report. In sections 3 and 4 we present the MSC results for the same testing set with and without extinction respectively. Finally, we close this report with a brief discussion in section 6.

3 Performance of MSC for data without extinction

As it was mentioned in the introduction, for the sample of simulated data without extinction a subset of 10,000 BP/RP spectra were used to train the MSC models in order to extract the brightness ratio of the two stars of the system, the effective temperature, the luminosity and the gravity for the primary and the secondary star separately. These tests were performed for two values of G magnitude: 15 and 18.5. The results for both magnitudes are presented in figures 3-5, where the difference between the predicted and real values is presented against the real

Table 1: Summary of the performance of the regression models.

AP	Code	G (mag)	A_0 (mag)	$\frac{mean(predicted-real)}{mean(real)}$	$\frac{rms(predicted-real)}{mean(real)}$
Teff1	MSC	15.0	0	-9.90e-04	1.93e-02
	MSC	18.5	0	-1.94e-03	4.02e-02
	MSC	15.0	1-10	-1.76e-02	2.25e-01
	MSC	18.5	1-10	-3.21e-02	3.41e-01
	MSC	20.0	1-10	-5.20e-02	4.19e-01
	GSP-phot	15.0	0	-7.19e-03	6.34e-02
	GSP-phot	15.0	1-10	-8.37e-03	3.99e-01
Teff2	MSC	15.0	0	-6.01e-03	9.83e-02
	MSC	18.5	0	-1.09e-02	1.24e-01
AP	Code	G (mag)	A_0 (mag)	$mean(predicted-real)$	$rms(predicted-real)$
logg1	MSC	15.0	0	1.50e-03	3.68e-02
	MSC	18.5	0	4.57e-04	7.43e-02
	GSP-phot	15.0	0	-4.17e-01	6.69e-01
lum1	MSC	15.0	0	1.39e-03	4.94e-02
	MSC	18.5	0	6.72e-05	1.15e-01
logg2	MSC	15.0	0	7.67e-03	8.95e-02
	MSC	18.5	0	-1.97e-02	1.33e-01
lum2	MSC	15.0	0	-1.14e-02	3.44e-01
	MSC	18.5	0	-3.27e-02	4.51e-01
Brightness Ratio	MSC	15.0	0	1.43e-02	3.37e-01
	MSC	18.5	0	3.75e-02	4.47e-01
	MSC	15.0	1-10	5.97e-03	5.01e-01
	MSC	18.5	1-10	-1.48e-02	6.42e-01
	MSC	20.0	1-10	-5.15e-02	7.41e-01
A_0	MSC	15.0	1-10	-3.07e-03	1.22e-01
	MSC	18.5	1-10	-1.65e-02	3.46e-01
	MSC	20.0	1-10	1.14e-02	6.48e-01
	GSP-phot	15.0	1-10	-4.67e-01	1.33e+00

values of each AP. In table 1 we have gathered the results of all the tests included in this report for an easier comparison.

From figures 3 and 4 as well as table 1 we see that the predictions of the APs for the primary star are in most cases very accurate while in the case of the secondary star the results are very poor. More specifically for G=15 mag the luminosity of the primary star can be extracted with very small errors for the whole range of values of this AP. In the case of Teff and logg of the primary star this is also true for low temperatures (<10,000 K) and large gravities (>4 dex), which correspond to areas where our training sample is more dense and the models better trained. This is very obvious for the case of logg>4.4 dex, where the sample is very dense for all values of temperatures (figure 1), and as a result the residuals of the predictions have a very small variance around 0. Another example is the dispersion of the residuals of effective temperature, which becomes much larger after approximately 7,500 K, i.e. the point after which the training data become very sparse.

For the case of the secondary star we see that the effective temperature is estimated with large errors and always around the value of 4000 K. This is again an effect of the distribution of APs in the training sample (figure 1) which includes very few stars with higher temperatures. The results are very similar for the case of luminosity, which is highly correlated with the temperature of the star. Finally, the estimation of logg parameter seems to give also poor results, which was expected since the effect of this parameter in the resulting spectrum is more weak and its range of values in this library is very narrow.

For the case of the brightness ratio between the two stars (figure 5) we see that the results are quite good. However this might be due to a correlation of this parameter with the characteristics of the primary star and the very narrow range of the parameter values of the secondary star. To test this hypothesis, in figure 5 we also present the brightness ratio against the effective temperature and the luminosity of the primary star. Even though a correlation between these parameters is present in these plots, it is not as strong as we have expected based on the good estimations of the brightness ratio and the poor performance in the extraction of the luminosity of the secondary star by MSC.

Finally, as it was expected the results become worse as the stars become fainter and we move from G=15 mag to G=18.5. The parameters that seem to suffer the most from this change are the effective temperature and the luminosities.

All the above residuals were also plotted against the brightness ratio parameter in order to investigate if the results improve when the two stars are of similar masses or when the primary star is much more massive than the secondary. However, this comparison showed that the performance of MSC is almost independent of the brightness ratio between the two stars and that the impact of the amount of the training data in each parameter space is stronger than all the other effects. This distortion of the global fitting caused by local density variations is probably a more general weakness of the SVMs.

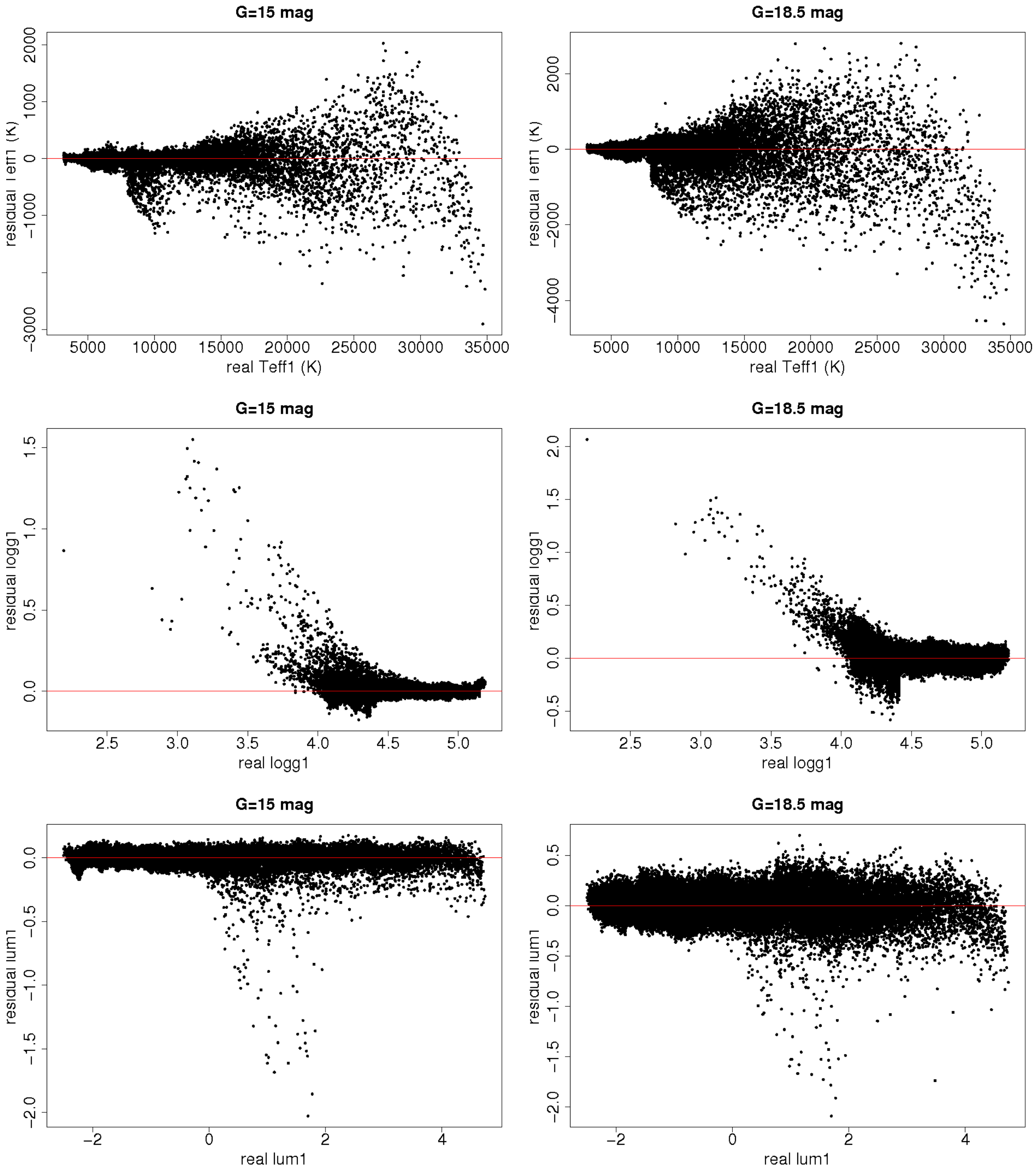

Figure 3: The performance of MSC in the prediction of the most significant APs of the primary star. The residuals of the APs vs. their real values. In this sample extinction was fixed to zero.

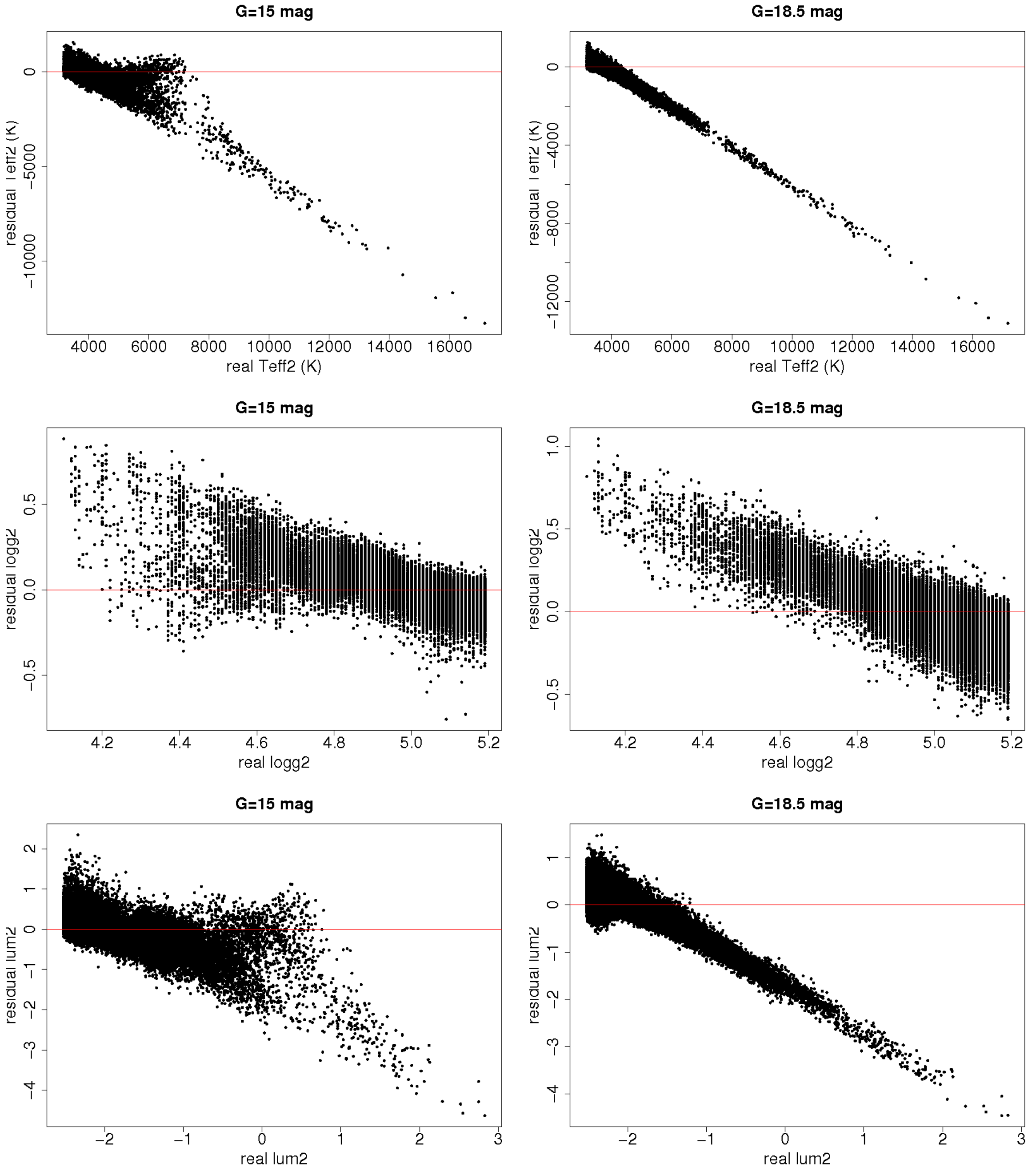

Figure 4: The performance of MSC in the prediction of the most significant APs of the secondary star. The residuals of the APs vs. their real values. In this sample extinction was fixed to zero.

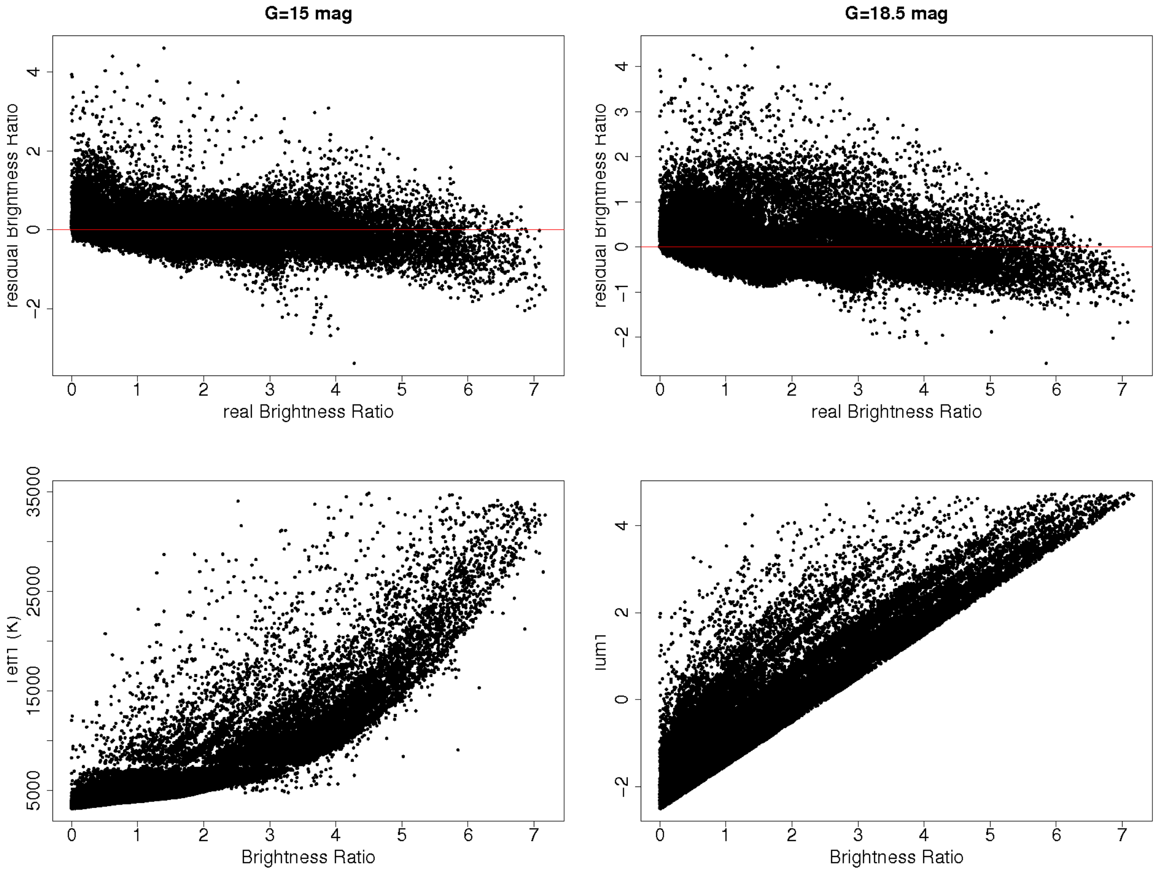

Figure 5: **Top:** The performance of MSC in the prediction of the brightness ratio. The residuals of the APs vs. their real values. In this sample extinction was fixed to zero. **Bottom:** Brightness ratio vs. temperature (left) and brightness ratio vs. luminosity of the primary star in the testing set used here (right).

4 Performance of MSC for data with extinction

In this section we present the results of MSC for the estimation of three main APs of the binary stars. The MSC models are trained and applied to the same sets of BP/RP spectra as in section 3, but this time the spectra have been artificially reddened using a grid of random values of A_0 in the range from 1 to 10 mag. The three APs that were estimated with this method are the effective temperature of the primary star, the brightness ratio and the extinction parameter. We limited our tests only to those parameters, since for most of the other APs the accuracy was quite low even in the case of extinction free data. The tests were run for 3 different G magnitudes: 15, 18.5 and 20 mag and the results are presented in figure 6 and table 1.

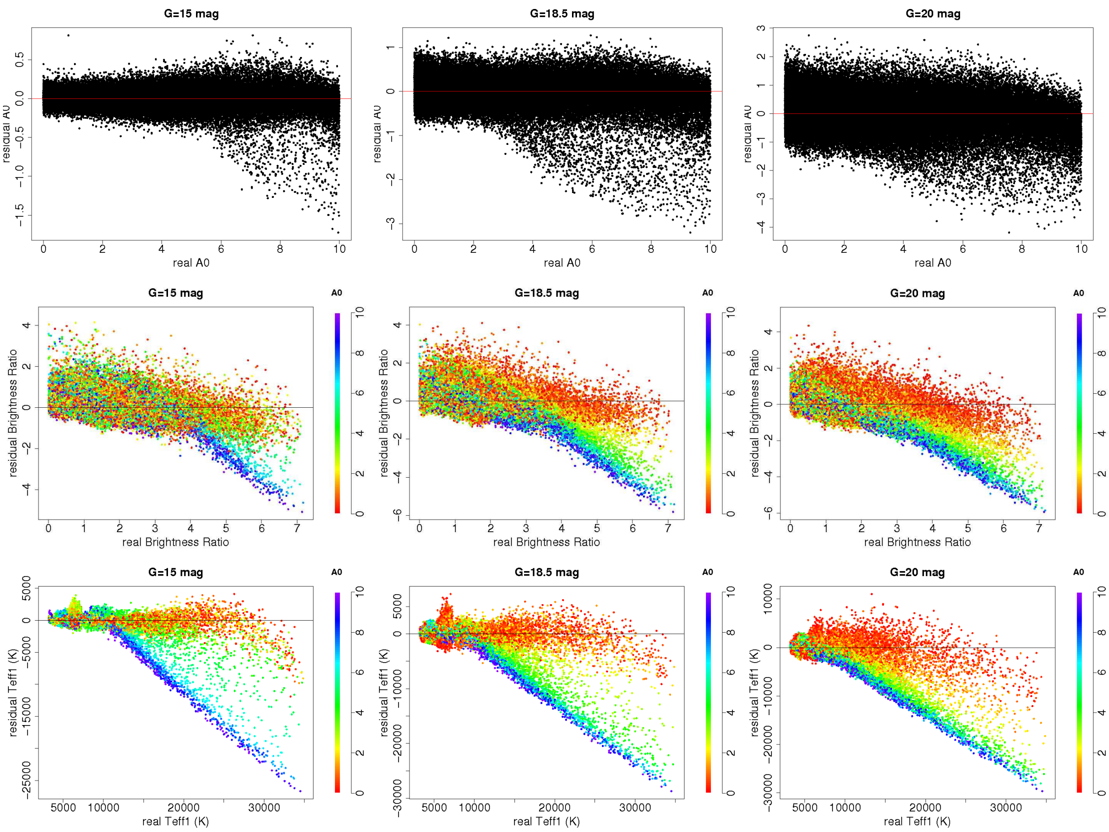

Figure 6: The performance of MSC in the prediction of the most significant APs of binary stars. The residuals of the APs vs. their real values. In this sample extinction is included. In the diagrams for the brightness ratio and temperature, the colors correspond to the true values of the A_0 parameter (see color bars).

Since this is the first time we applied MSC to data with reddening it is interesting to see the results for the estimation of this parameter. The results show that A_0 can be extracted quite accurately, especially for G=15 mag. For fainter objects the dispersion of the residuals between real and predicted values becomes larger but the results are still good with respect to the magnitude. This seems to be the case also for the brightness ratio and temperature parameters. Of course for both APs the results are worse than in the case of extinction free spectra and they become less accurate as we move to greater magnitudes. In these plots we also see the presense of some features (lines) that occur from a certain point and after (A_0 >6 mag, brightness ratio>4.5 and Teff>12500 K approximately) and they become stronger as we move to fainter objects. For all cases the binary stars populating these features are the ones with high temperatures and they are the same ones that cause the higher dispersion in the results without extinction (see figure 3). However, the results in this section seem to be worse, and in the cases of temperature and brightness ratio estimation MSC seems to be almost not trained for this subset of the data (see the strong lines that occur in the plots of figure 6).

To investigate the impact of extinction in these results we have color coded the true values of A_0 in the above diagrams. From these plots we see that the features under discussion correspond to stars with high values of extinction in addition to high temperatures. For G=15 mag we see that MSC results are very poor for temperatures above 12500K and A_0 greater than approximately 6 mag. As the magnitude increases these features are populated by stars of the same temperatures but lower values of extinction as well (above 4 and 2 mag for G=18.5 and 20 mag respectively). This is more obvious in figure 7 where with blue, green and red points we represent the binary stars that populate the features in the temperature plots of figure 6, for G=15, 18.5 and 20 mag respectively. From this plot we see that for those values of temperature and extinction our sample of spectra is not very dense which results to a not well trained model for this range of parameters. Of course some of these results might be due to degeneracies between temperature and extinction parameters. A further investigation for the effects of degeneracies is needed and should be done in the future. In the same figure (7) we also present the same stars in the brightness ratio vs. temperature diagram in order to investigate the role of the brightness ratio in the bad estimations. Once again we see that the impact of the brightness ratio in our results is very weak.

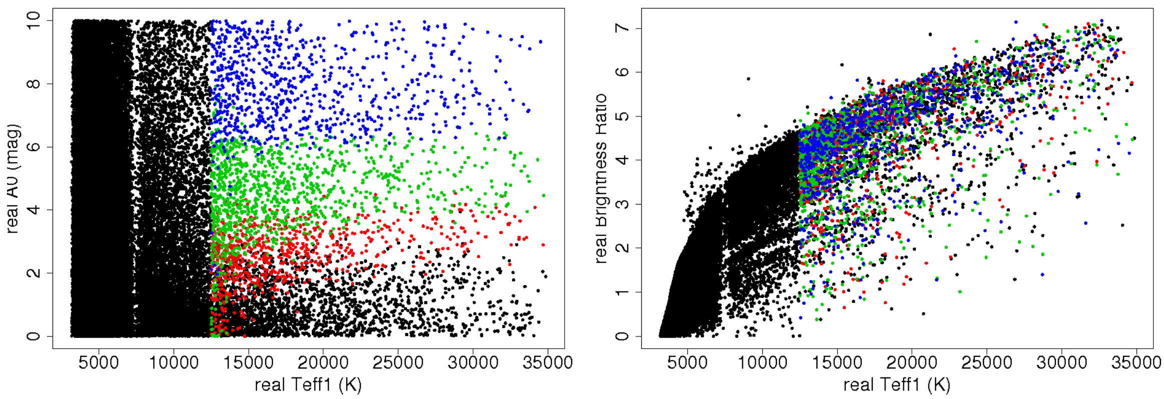

Figure 7: The effective temperature of the primary star (right) and the brightness ratio (left) vs. the value of A_0. With blue, green and red points we represent the binary stars that populate the strong features (lines) with wrong estimations in fig. 6, for G=15, 18.5 and 20 mag respectively.

5 Comparison with GSP-phot

For the comparison of the results above with the the ones performed by GSP-phot we performed tests for simulated spectra that correspond to G magnitude 15 with and without extinction. GSP-phot models were trained using 6000 BP/RP spectra of single stars (see figure 2) and applied to the same testing sets of binaries used in sections 3 and 4. Since GSP-phot is not able to predict parameters of the secondary star (for which the performance of MSC is quite poor) we tried to estimate the effective temperature and the gravity of the primary star. The results for extinction free data can be seen in figure 8.

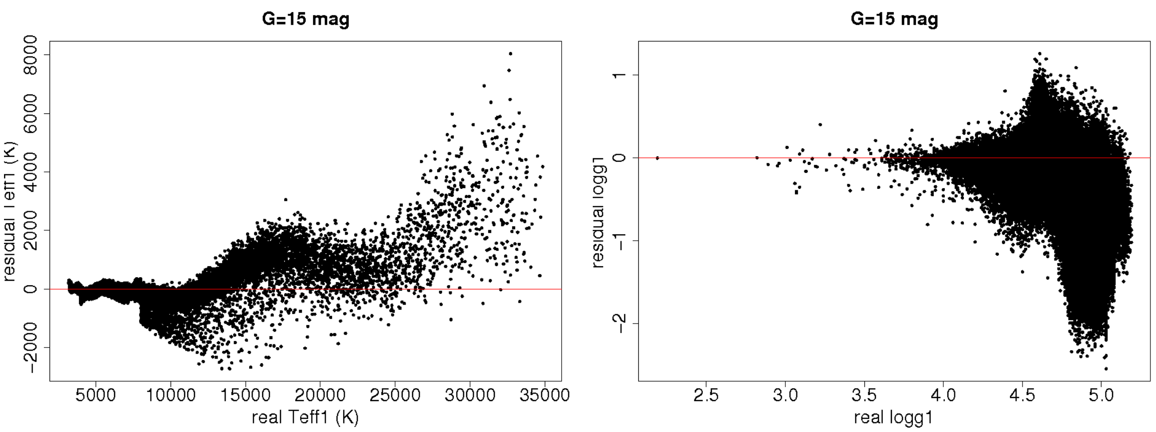

Figure 8: The performance of GSP-phot in the prediction of the most significant APs of binary stars. The residuals of the APs vs. their real values. In this sample extinction was fixed to zero.

From this figure we see that the results are quite poor for both parameters (for comparison with MSC results see figure 3 and table 1). Especially for the case of effective temperature of hot stars and surface gravity of massive stars. For the logg parameter the results of GSP-phot seem to be better than the ones of SMC for stars with low mass.

In the same way we applied GSP-phot to data of binary stars with extinction. The results of GSP-phot for the estimation of the extinction parameter A_0 and the effective temperature for the binary stars of G=15 mag with extinction are presented in figure 9 and table 1. The GSP-phot models for these tests have been trained with 6000 simulated spectra of single stars which included extinction for various values of A_0 (see figure 2). By comparing these results with the ones extracted by MSC we see that GSP-phot is estimating with better accuracy the APs with large values while it is extracting very poor results for low values of extinction and temperature. Additionally, in contrast to figure 6 we see that GSP-phot tends in many cases to overestimate the temperature of hot stars for which MSC usually underestimates, while the presence of a group of stars with high extinction parameter that is underestimated is not obvious anymore. The former might be a result of the higher temperatures that are included in the sample used to train the GSP-phot.

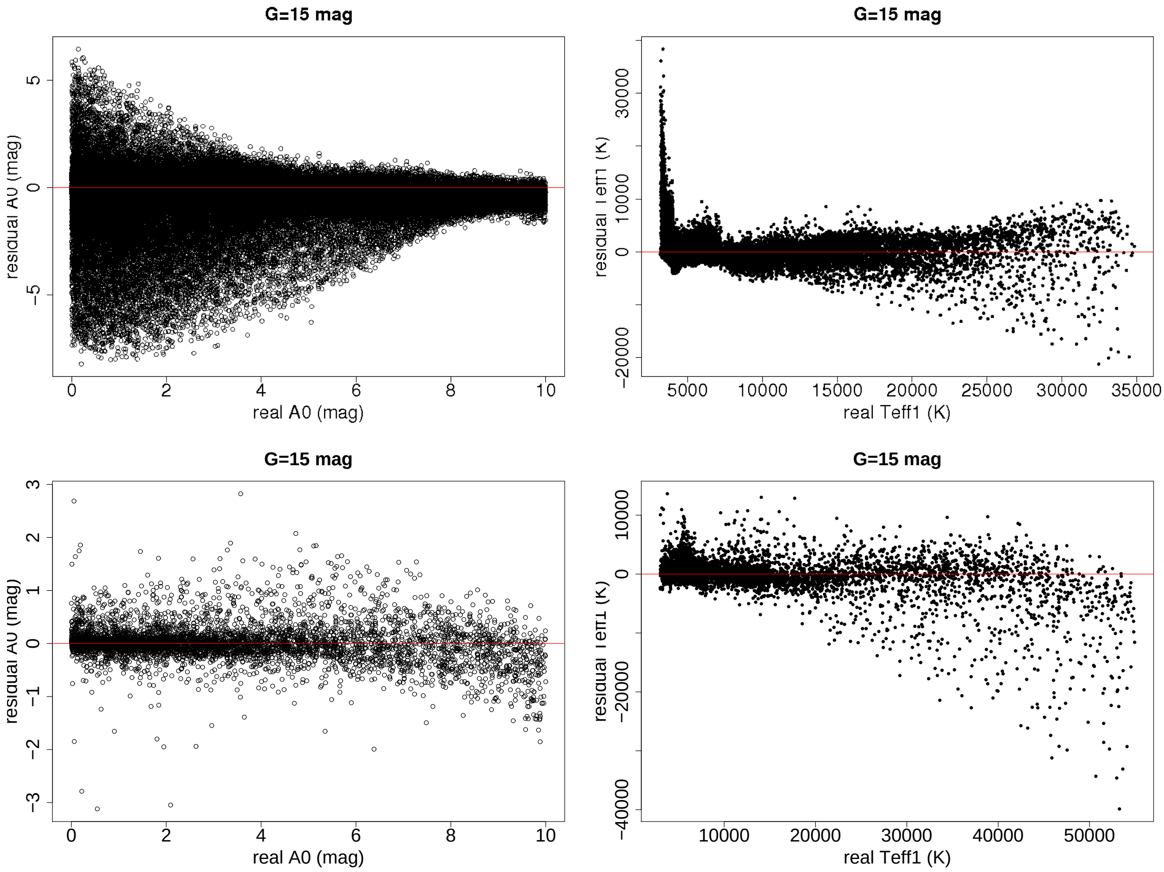

Figure 9: The performance of GSP-phot in the prediction of the most significant APs of binaries (top) and single stars (bottom). The residuals of the APs vs. their real values. In this testing sample extinction is included.

In order to check if this is a result of the different nature of objects between training and testing sets we applied the same GSP-phot models to a small set (6000 spectra) of single stars. The results are presented again in figure 9 and they show that the performance of GSP-phot when applied to reddened spectra of single stars is very good. These results, in addition to the comparison to the MSC results imply that GSP-phot models are not suitable for the analysis of Gaia spectra of binary stars.

To investigate in more detail the nature of the differences in the GSP-phot results for binaries and single stars and try to explain why the performance is poor for low and not large values of temperature and extinction we made some more tests. First we checked the relation between poor results for A_0 and temperature parameters. This was made by checking the location of the binaries with A_0 residuals greater than 1 mag and less than -2 mag (red points in figure 10) on the diagram of the results for the Teff (right plot of figure 10). In these plots we see that the bad predictions in the two quantities are highly correlated and that GSP-phot overestimates (or underestimates) the temperature for the same group of stars for which it overestimates (or underestimates) the A_0. Both groups of binaries consist of cool stars with values of effective temperature for the primary star up to 4750 K.

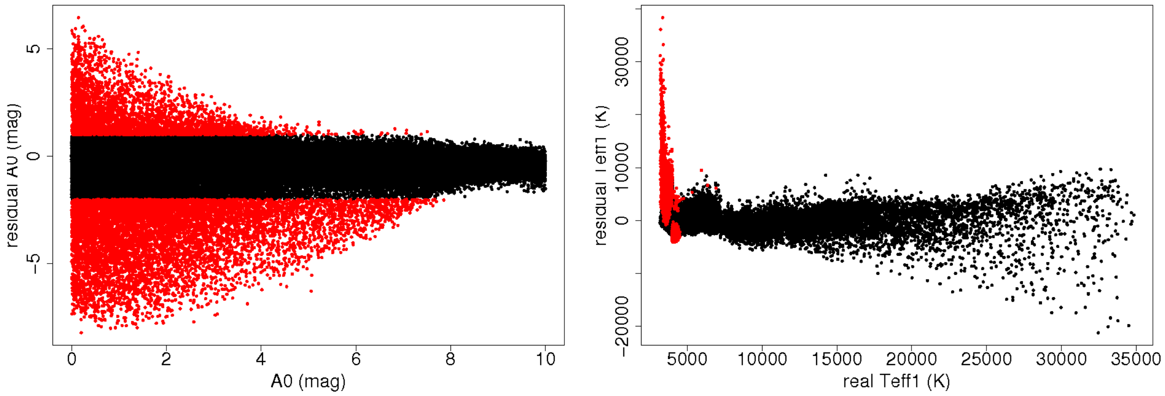

Figure 10: The performance of GSP-phot in the prediction of the most significant APs of binaries. The residuals of the APs vs. their real values. The red points represent the binaries with A_0 less than -2 mag or larger than 1 mag. In this testing sample extinction is included.

In order to understand better the difference between those binaries and the rest with cool components we enlarged the diagram presenting the results for the effective temperature (figure 11). In this plot we see that there is a hard cut in the results at the point of 4000 K. This cut is also present in the case for the same data with no extinction (right plot in figure 11). This might be due to the change in libraries at this temperature from MARCS, above 4000 K, to BaSeL, for lower temperatures. This is also implied by the fact that the points with underestimated temperature and extinction are the ones with temperature a little above 4000 K. These stars must have a primary component from the MARCS library and a secondary from the BaSeL library. This combination seems to cause problems to GSP-phot which is trained only by single stars. At this point we should mention that this cut is not present in the results of the MSC for the same sample.

To see if the spectra of these different groups of binaries have significant differences and to compare them to the those of cool single stars we also present the mean spectrum of each group in figure 12. In this figure the colors are the same as in figure 11 for the different groups of binary stars and with blue lines we represent the mean spectra of the single stars in the training set with temperatures in these ranges. From the plot corresponding to data with extinction and for temperature less than 4000 K (top left plot in figure 12) we see that indeed the green and blue spectra are very similar and therefore it was easy for GSP-phot to recognize these binary stars as cool stars. This is not the case for the black mean spectrum which as we see is a little bluer than the other two and includes much stronger features in its red part of the spectrum than in the other cases. For the stars with temperatures in the range from 4000 to 4750 K we see that once again green and blue spectra are very similar. The very few (only 22) spectra that are used to produce the mean black spectrum seem to be a lot redder than the spectra of the

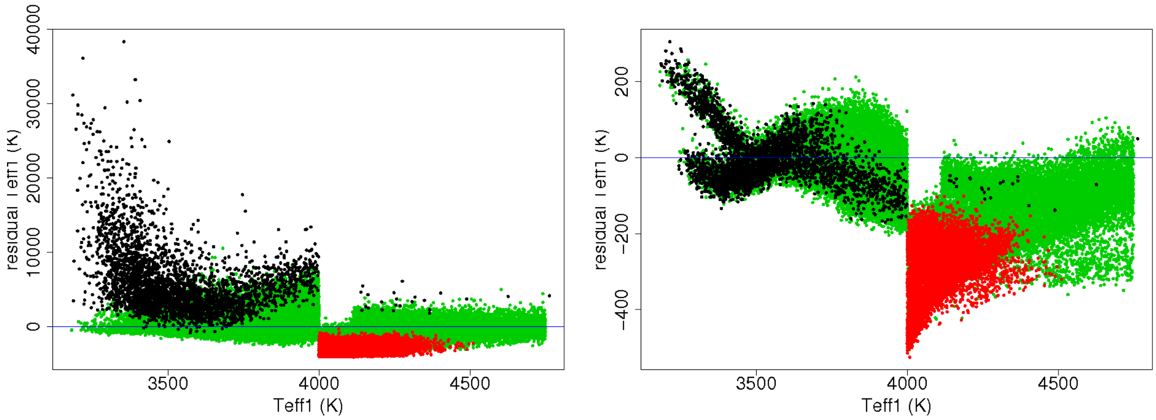

Figure 11: Enlarged view of the performance of GSP-phot in the prediction of the effective temperature spectra with (left) and without extinction (right). With black, red and green points we represent the binary stars with A_0 residuals larger than 1 mag, less than -2 mag, and the rest of the stars with Teff1 in this range respectively. When extinction is not included (right), the colors indicate the same set of binary stars as in the left diagram.

other groups. This leads GSP-phot to overestimate the A_0 parameter and due to temperature-extinction degeneracy overestimate the temperature as well. The opposite is the case for the red spectra were the strong features in the red part of the spectrum imply a low temperature.

In the same figure (12) we also present for comparison the mean spectra of the same groups of stars when extinction is not taken into account. We should note that each spectrum has been reddened using a random value of A_0.

6 Discussion and conclusions

From the results presented above it is obvious that the current version of MSC can estimate the most significant parameters of the binary stars (brightness ratio, Teff, luminosity and logg for the primary star) quite accurate for data without extinction. However, the accuracy is becoming lower for very hot stars or stars with low masses, since our sample includes a very small number of stars with these characteristics. That was also the problem for the case of the metallicity parameter ([Fe/H]) which we were not able to estimate with small errors since our data were simulated only for 4 discrete values of this parameter. Moreover for the case of alpha elements abundances only zero value was available.

For the secondary star the results showed that even for extinction free spectra the results were very poor. This implies that new methods should be explored in order to improve the results for the secondary star. This is not an easy task since the impact of the primary star in the spectrum of the system is much stronger than the one of the secondary. In addition the secondary stars seem to cover a very narrow and sparse area of the APs space compared to the primary star.

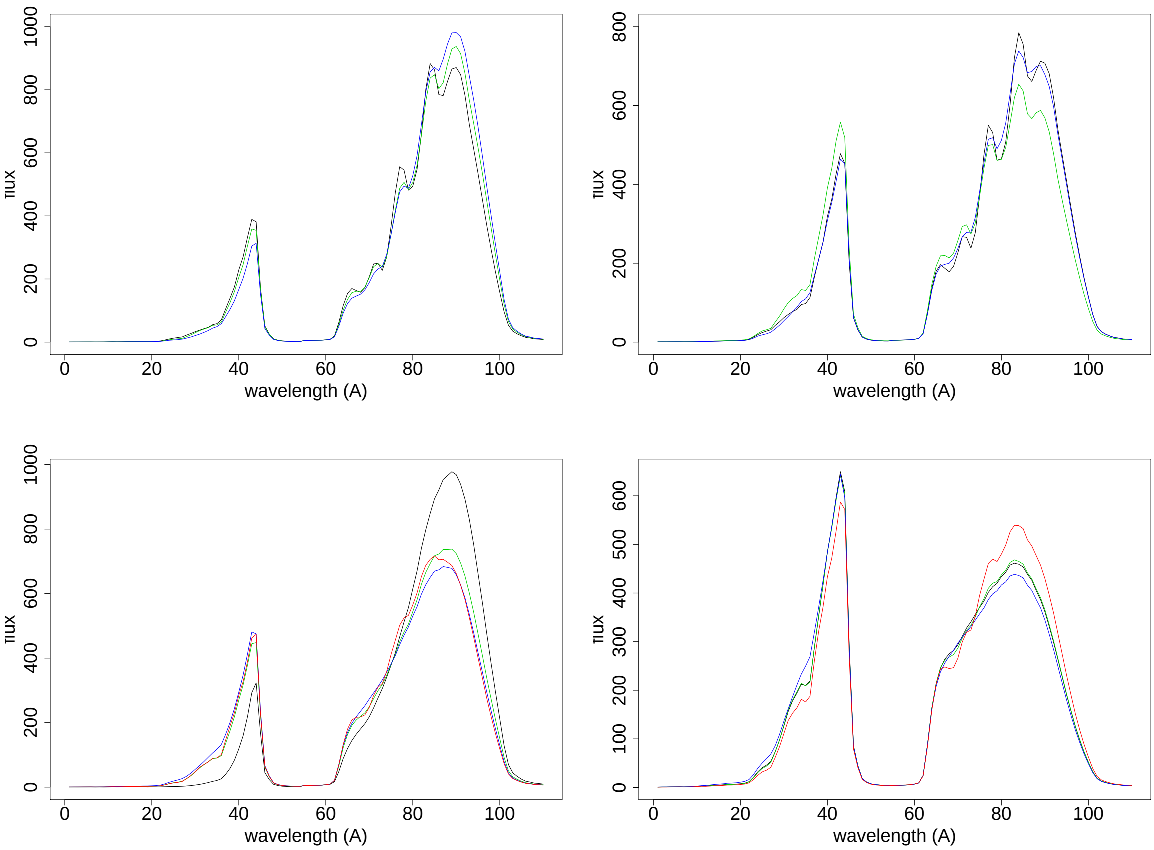

Figure 12: Mean spectra for the groups of binary stars of figure 11 for data with (left) and without extinction (right). The top panel presents the results for stars with Teff less than 4000 K while the bottom for Teff from 4000-4750 K. With black, red and green lines we represent the binary stars with A_0 residuals larger than 1 mag, less than -2 mag, and the rest of the stars with Teff1 in this range respectively. With blue lines we present the mean spectrum of single stars in the training set with temperatures in the corresponding ranges. When extinction is not included (right), the colors indicate the same set of binary stars as in the left diagrams.

When extinction was included in our data the estimation of parameters like the effective temperature and the gravity of the primary star were still quite good. Problems appear again in the areas were our sample is less dense, while part of these problems might be due to degeneracies between temperature and extinction. This later issue needs further investigation.

Another important result of the tests performed here was that the results do not seem to strongly corelate with the brightness ratio between the two stars of the binary system. However, we should keep in mind that this might be an effect of the grid values in our sample.

The results produced by MSC were also compared with tests ran by GSP-phot models extracted by training on single stars data and tested on the same set of BP/RP spectra of binary stars with and without extinction. Since the MSC code is basically the GSP-phot but extended for more parameters, this gave us the opportunity to test how much the results depend on the training sample used. The comparison showed that in all cases the results of MSC are more accurate. Especially when data with extinction was used, GSP-phot performance is quite poor for binaries with low extinction and temperature. These results are probably due to the different nature of the objects used to train the GSP-phot models. For the case of binary stars with cool components it is possible that the bad results of GSP-phot are caused by the construction of the binary stars spectra using stellar spectra from different libraries. For all the above reasons, MSC is a more suitable algorithm than GSP-phot for the analysis of Gaia spectra of binaries stars, even though the two algorithms mainly differ in the type of objects used to train them. This does not mean that MSC should just continue developing in parallel with GSP-phot but with more APs. The algorithm should change in order to achieve the best possible performance for this type of objects.

In the future we are planning to test how the use of parallax or information from H-R diagram could help the improvement of the results (some ideas on this subject can be found in GAIA-C8-TN-MPIA-CBJ-049). Additionally we should investigate how the knowledge of some APs that could be provided by other CUs could be used by MSC (e.g. Mass ratios, or other APs that could be in principle provided by CU4). Moreover we should test ways of using the APs of the primary star, which seem to be estimated already accurately by MSC, to help the prediction of the APs of the secondary star. One possible way of doing this is by using subclassifiers for different ranges of values of the APs of the primary star. Finally, the ILIUM algorithm (Bailer-Jones 2010) should be applied to binary stars.

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