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Gaia DR3. Absolute flux calibration in the Vega system.

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Abstract

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1 The sample of stars

A best sample of library stars from the SPSS, CALSPEC, NGSL, UVES_POP, and XSL libraries were selected for our work on calibration of BPRP spectra:
147 stars from the SPSS library have BP/RP spectra, 101 from the CALSPEC library, 381 stars from the NGSL library, 302 stars from the UVES_POP library, and 292 stars from the XSL library have BP/RP spectra.

By retaining stars non saturated, single, and by excluding peculiar stars confused or with emission lines,
there remain 68 (SPSS), 65 (CALSPEC), 198 (NGSL), 118 (UVES), and 232 (XSL) stars, respectively. Furthermore, by considering only stars with average flux deviation between the high-resolution spectra and the Gaia DR3 BP/RP spectra within 1%, there remain 27 (SPSS), 33 (CALSPEC), 16 (NGSL), 24 (UVES), and 24 (XSL) stars.

1.1 Passbands

The Gaia DR3 passbands are identical to the Gaia EDR3 passbands for G, BP, and RP and are taken from EDR3 passbands.

1.2 Synthetic photometry

By using the best library stars, synthetic photometry was performed to check the absolute flux calibration of the Gaia Photometry and of the Gaia low-resolution spectra.

Two codes were used an IDL code witten by Maria Messineo and a python code, Pyphot, freely distributed by Dr. Fouesneau. The code has been tested and used already by several groups, for example, see the work of Lahén et al. (2022).

1.2.1 IDL code

Given the two vectors wave and flux of each considered spectrum, finite datapoints were selected. The filter transmission curves were resampled on the same wave grid as the spectrum. The total transmitted flux was estimated with the trapezoidal method, as shown in Fig. 1. The formulas for a photon-dominated detector are used, following the equations of Bessell & Murphy (2012).

Following Gaia, the flux-calibrated CALSPEC spectrum of Alpha Lyr (alpha_lyr_mod_002.fits) is used. The zeropoints for the G, BP, and RP bands are 21.512696, 20.988515, 22.239332 mag (for flux densities in erg/s/cm2/A), respectively, when assuming zero magnitudes. If the Vega spectrum is rescaled to obtain flux = 3.62286 10^{-11} W m^{-2} nm^{-1} at the wavelength λ = 550.0 nm, a constant decrease of the absolute module of the ZPs of 0.0225716 mag is obtained. The zeropoints become 21.490125, 20.965944, 22.216762 mag, respectively.

If one would assumes the current model of Alpha Lyr (mode_04.fits), one would obtain these shifts of zeropoint
Δ ZP_G=0.00926781 mag mod2.fits-mod4.fits
Δ ZP_BP=0.0142517 mag mod2.fits-mod4.fits
Δ ZP_RP=−0.000947952 mag mod2.fits-mod4.fits.

	without scaling			scaled			comment
Data	ZP_G	ZP_BP	ZP_RP	ZP_G	ZP_BP	ZP_RP	
alpha_lyr_stis_011.fits	21.502980	20.973107	22.241177	21.488177	20.958304	22.226374	current stis
alpha_lyr_stis_003.fits	21.502330	20.976098	22.233063	21.486029	20.959797	22.216762	old stis
alpha_lyr_mod_004.fits	21.503428	20.974264	22.240281	21.490485	20.961322	22.227339	current mod
alpha_lyr_mod_002.fits	21.512696	20.988515	22.239332	21.490125	20.965944	22.216762	adopted by Gaia

```
for jj=1L, n_elements(wave)-2 do begin
  bin[jj]=(wave[jj+1]-wave[jj])
  funcG[jj]=((flux[jj+1]*restransflt[jj+1]*wave[jj+1])+(flux[jj]*restransflt[jj]*wave[jj]))*0.5
  funcBP[jj]=((flux[jj+1]*restransBP[jj+1]*wave[jj+1])+(flux[jj]*restransBP[jj]*wave[jj]))*0.5
  funcRP[jj]=((flux[jj+1]*restransRP[jj+1]*wave[jj+1])+(flux[jj]*restransRP[jj]*wave[jj]))*0.5
  denG[jj] =((restransflt[jj+1]*wave[jj+1])+(restransflt[jj]*wave[jj]))*0.5
  denBP[jj]=((restransBP[jj+1]*wave[jj+1])+(restransBP[jj]*wave[jj]))*0.5
  denRP[jj]=((restransRP[jj+1]*wave[jj+1])+(restransRP[jj]*wave[jj]))*0.5
endfor
bin[0]=bin[1]
bin[n_elements(wave)-1]=bin[n_elements(wave)-2]

la=where(wave gt 320 and wave lt 1050,cctot)
tot=total(funcG[la]*bin[la], /NaN)
tot_den=total(denG[la]*bin[la],1, /NaN)
Gmag=-2.5*alog10(tot/tot_den)+ZP_G

la=where(wave gt 325 and wave lt 750.,cctot)
tot=total(funcBP[la]*bin[la], /NaN)
tot_den=total(denBP[la]*bin[la],1, /NaN)
BPmag=-2.5*alog10(tot/tot_den)+ZP_BP

print, minmax(wave)
la=where(wave gt 610.00 and wave lt 1080.00,cctot)
tot=total(funcRP[la]*bin[la], /NaN) ;corretta vuole zero point in Jy
tot_den=total(denRP[la]*bin[la],1, /NaN)
RPmag=-2.5*alog10(tot/tot_den)+ZP_RP

;unit in erg/s/cm2/A
ZP_G=-21.502980
ZP_BP=-20.973107
ZP_RP=-22.241177
```

Fig. 1. The trapezoidal method in the IDL code.

1.2.2 Gaia DR3 zeropoints

For the Gaia external calibration, Riello et al. (2021) use the Vega spectrum (alpha_lyr_mod_002.fits) from the CALSPEC Calibration Library of 2013-2015. The spectrum is rescaled to obtain flux density = 3.62286 10^{-11} W m^{-2} nm^{-1} at the wavelength λ = 550.0 nm, which is assumed as the flux of an unreddened A0V star with V = 0 mag. The following Zeropoint for synthetic photometry in the VEGAMAG system are given:
ZP_G=−26.48986 mag (for flux densities in [W/m2/nm]),
ZP_BP=−25.96551 mag,
ZP_RP=−27.21639 mag.

1.2.3 Pyphot

Pyphot computes synthetic magnitudes in python. For the trapezoidal integration the numpy.trapz function is used, as shown in Fig. 2. Pyphot uses a Alpha Lyr spectrum (not specified), and assumes that Vega has magnitude 0 in any pass-band filter, and it provides a list of zeropoints. Zeropoints and passbands for DR3 are not listed, but they can be entered manually.

1.2.4 Comparisons of Zeropoints

The here calculated zeropoints (IDL code) appears precise, identical within errors to those officially released by Gaia DR3. By taking in account the different units used, the differences of the zeropoints given in Gaia DR3 and those estimated by Messineo (mod2 plus rescaling) are:
Δ ZP_G=−0.000265121 mag
Δ ZP_BP=−0.000434875 mag
Δ ZP_RP=−0.000371933 mag.

Indeed, in Table 2 the average difference between the synthetic magnitudes and the Gaia Phot DR3 magnitudes are listed. For the SPSS library, which is the main calibrator of the Gaia

```python
if 'photon' in self.dtype:
    a = np.trapz(_slamb[ind] * ifT[ind] * _sflux, _slamb[ind], axis=axis)
    b = np.trapz(_slamb[ind] * ifT[ind], _slamb[ind] )
elif 'energy' in self.dtype:
    a = np.trapz( ifT[ind] * _sflux, _slamb[ind], axis=axis )
    b = np.trapz( ifT[ind], _slamb[ind])
if (np.isinf(a).any() | np.isinf(b).any()):
    print(self.name, "Warn for inf value")
return a / b
```

Fig. 2. The trapezoidal method in the python code.

~/DUTY/Synth_G/pythot_NGSL_GaiaDR3.py (functions)

```
import pandas as pd
import numpy as np
from numpy  import array
import pyphot
from pyphot import unit
from pyphot import (unit, Filter)
import astropy
import math

file="/Users/mmessine/DUTY/Spectral_Libraries/NGSL/NGSL_GAIA-BPRP/NGSL-resultFITSbest.csv"
datacsv = pd.read_csv(file,delimiter=',')
dum=""


dfsel=datacsv[ (datacsv['comment'] == 'OK')  & (datacsv['flagsel'].between(1,1))]
names=dfsel['NGSL'].to_numpy()
namfits=dfsel['filefits'].to_numpy()
nsources = len(names)
meanG=dfsel['phot_g_mean_mag'].to_numpy()
meanBP=dfsel['phot_bp_mean_mag'].to_numpy()
meanRP=dfsel['phot_rp_mean_mag'].to_numpy()
frames =['Name', 'SyntG', 'SyntBP', 'SyntRP','ZP_G','ZP_BP','ZP_RP','dr3G','dr3BP','dr3RP']


ZP_G =21.490125
ZP_BP=20.965944
ZP_RP=22.216762

from astropy.table import Table
myname="GaiaEDR3_passbands_zeropoints_version2/passband.dat"
data = Table.read(myname, format='ascii')

waveG=data['col1'][np.where(data['col2'] < 99.)]
transmitG=data['col2'][np.where(data['col2'] < 99.)]

waveBP=data['col1'][np.where(data['col4'] < 99.)]
transmitBP=data['col4'][np.where(data['col4'] < 99.)]

waveRP=data['col1'][np.where(data['col6'] < 99.)]
transmitRP=data['col6'][np.where(data['col6'] < 99.)]

fG  = Filter(waveG,  transmitG, name='fG',  dtype='photon', unit='nm')
fBP = Filter(waveBP, transmitBP, name='fBP', dtype='photon', unit='nm')
fRP = Filter(waveRP, transmitRP, name='fRP', dtype='photon', unit='nm')


for i in range(nsources):
     myname=np.char.add(['/Users/mmessine/DUTY/Spectral_Libraries/NGSL/specs_513_fits/'],namfits[i]).item()
     print(myname)

     from astropy.table import Table
     data = Table.read(myname, format='fits')
     print(data)
     wave_nm=data['Wavelength']
     flux=data['Scattered Light & Slit Offcenter Corrected']


     wave_unit = wave_nm*unit['AA']
     wave_unit = wave_unit.to('nm')
     flux = flux * unit['erg/s/cm**2/AA']
```

Fig. 3. Pyphot code.

```

     fluxes=fG.get_flux(wave_unit, flux)* unit['erg/s/cm**2/AA']
     pippo=1. * unit['erg/s/cm**2/AA']
     vector=fluxes/pippo
     magG =  -2.5*math.log10(vector)-ZP_G


     fluxes=fBP.get_flux(wave_unit, flux,axis=-1)* unit['erg/s/cm**2/AA']
     pippo=1. * unit['erg/s/cm**2/AA']
     vector=fluxes/pippo
     magBP =  -2.5*math.log10(vector)-ZP_BP

     fluxes=fRP.get_flux(wave_unit, flux)* unit['erg/s/cm**2/AA']
     pippo=1. * unit['erg/s/cm**2/AA']
     vector=fluxes/pippo
     magRP =  -2.5*math.log10(vector)-ZP_RP

     lala=(names[i],magG, magBP, magRP,ZP_G,ZP_BP,ZP_RP,meanG[i],meanBP[i],meanRP[i])
     lala=np.asarray(lala)
     frames = np.vstack([frames, lala])

df = pd.DataFrame(frames,columns=['Name', 'SyntG', 'SyntBP', 'SyntRP','ZP_G','ZP_BP','ZP_RP','dr3G','dr3BP','dr3RP'])
df.to_csv("NGSL_pyphotDR3.csv")

```

Fig. 3. Continued: Pyphot code.

photometry, a difference of −0.001 mag is found between our synthetic G magnitudes and the Gaia DR3 G magnitudes, a difference of −0.004 mag for the BP-band, and a difference of +0.004 for the RP-band.

2 Synthetic magnitudes with BP/RP spectra

The same set of stars is used to estimate synthetic magnitudes from BPRP spectra. The estimated magnitudes are compared with the Gaia DR3 photometry in Table 4.

3 Results

- The absolute flux calibration of the BPRP spectra has the same accuracy then the Gaia DR3 photometry catalog. Indeed, for all libraries, but the XSL, the average differences and dispersions between the synthetic magnitudes from BPRP spectra and the Gaia Phot DR3 magnitudes are consistent with the average differences and dispersions between the synthetic magnitudes from the library spectra and the Gaia Phot DR3 magnitudes.
- The XSL library cannot be used as a flux calibrator source. For example, Δ G (XSL spectra)=−0.023 mag with σ=0.013 mag, while Δ G (BPRP spectra)= −0.010 mag with σ=0.004 mag.
- For the synthetic magnitudes, within errors, the actual choice of the CALSPEC Alpha Lyr fits (mod_2 or mod_4) is irrelevant.

sectionReferences

Bessell, M. & Murphy, S. 2012, PASP, 124, 140
Lahén, N., Naab, T., & Kauffmann, G. 2022, MNRAS, 514, 4560
Riello, M., De Angeli, F., Evans, D. W., et al. 2021, A&A, 649, A3

Table 1. Summary of the difference between the synthetic magnitudes (IDL) and the Gaia Phot DR3 magnitudes. Alpha Lyr (mod2) rescaled.

Library	N_*	Synt_IDL-Phot_DR3					
		Δ G	σ	Δ BP	σ	Δ RP	σ
XSL	24	−0.025	0.013	−0.037	0.020	−0.009	0.009
UVES_POP	24	−0.007	0.010	0.008	0.010	−0.012	0.011
NGSL	16	−0.013	0.010	−0.011	0.008	−0.007	0.011
SPSS	27	−0.001	0.006	−0.004	0.006	+0.004	0.005
CALSPEC	33	−0.008	0.006	−0.011	0.005	0.001	0.003

Table 2. Summary of the difference between the synthetic magnitudes (pyphot) and the Gaia Phot DR3 magnitudes. Alpha Lyr (mod2) rescaled.

Library	N_*	Synt_IDL-Phot_DR3					
		Δ G	σ	Δ BP	σ	Δ RP	σ
XSL	24	−0.025	0.013	−0.037	0.020	−0.009	0.009
UVES_POP	24	−0.007	0.010	0.008	0.010	−0.012	0.011
NGSL	16	−0.013	0.010	−0.011	0.008	−0.007	0.011
SPSS	27	−0.001	0.006	−0.004	0.006	+0.004	0.005
CALSPEC	33	−0.008	0.006	−0.011	0.005	0.001	0.003

Pyphot performs identically to our IDL code in all case.

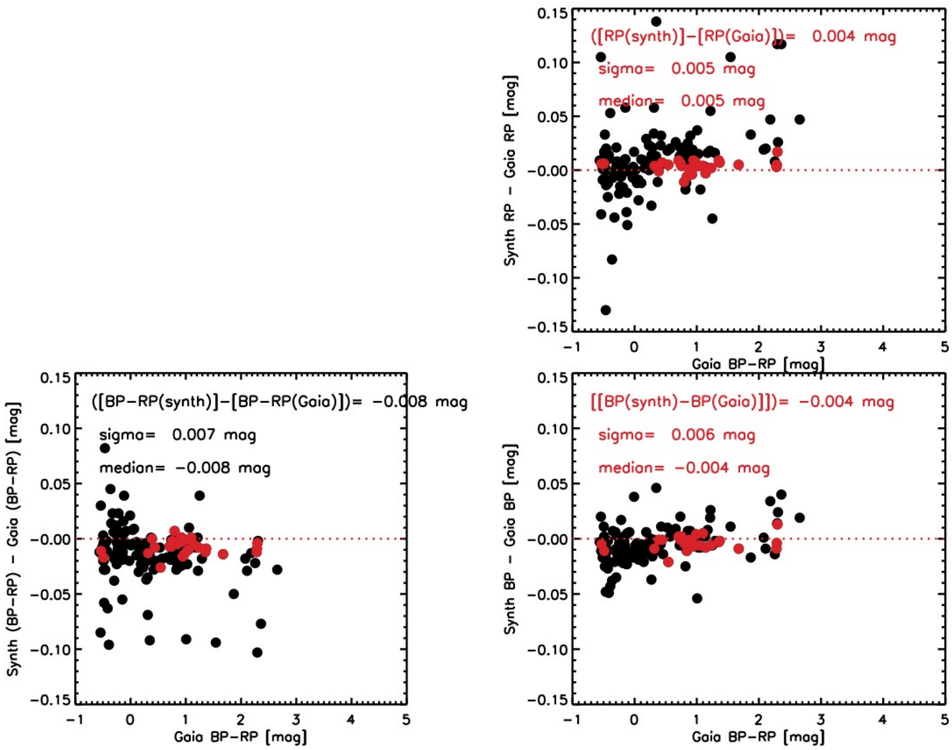

Fig. 4. SPSS library: Synthetic G, BP, and RP magnitudes vs. Gaia DR3 G, BP, and RP magnitudes. Stars flagged as "OK" are plotted in black. In red are those with average flux deviation between the BP/RP spectra and XSL spectra within 1%.

Table 3. Summary of the difference between the synthetic magnitudes (IDL) and the Gaia Phot DR3 magnitudes. Alpha Lyr (stis11) rescaled.

Library	N_*	Synt_IDL-Phot_DR3					
		Δ G	σ	Δ BP	σ	Δ RP	σ
XSL	24	−0.023	0.013	−0.029	0.020	−0.019	0.010
UVES_POP	24	−0.005	0.010	0.015	0.010	−0.021	0.011
NGSL	16	−0.011	0.010	−0.003	0.008	−0.017	0.011
SPSS	27	+0.001	0.006	+0.004	0.006	−0.006	0.005
CALSPEC	33	−0.007	0.006	−0.003	0.005	−0.007	0.006

Table 4. Summary of the difference between the synthetic magnitudes from BPRP spectra and the Gaia Phot DR3 magnitudes. Alpha Lyr (mod2) rescaled.

Library	N_*	Synt_IDL_BPRPspectra-Phot_DR3					
		Δ G	σ	Δ BP	σ	Δ RP	σ
XSL	24	−0.010	0.004	−0.008	0.019	−0.006	0.004
UVES_POP	24	−0.007	0.010	0.007	0.010	−0.012	0.011
NGSL	16	−0.013	0.010	−0.011	0.008	−0.007	0.011
SPSS	27	−0.004	0.005	−0.008	0.006	−0.002	0.001
CALSPEC	33	−0.006	0.007	−0.005	0.007	−0.004	0.003

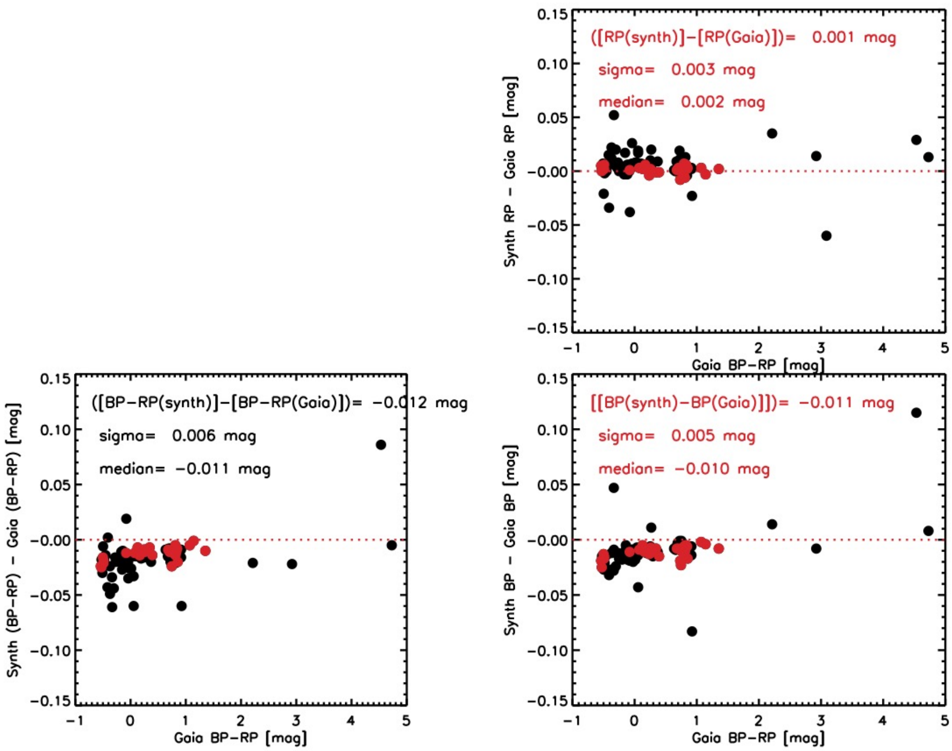

Fig. 5. CALSPEC library: Synthetic G, BP, and RP magnitudes vs. Gaia DR3 G, BP, and RP magnitudes. Only stars flagged as ”OK” are plotted in black. In red are those with average flux deviation between the BP/RP spectra and CALSPEC spectra within 1%.

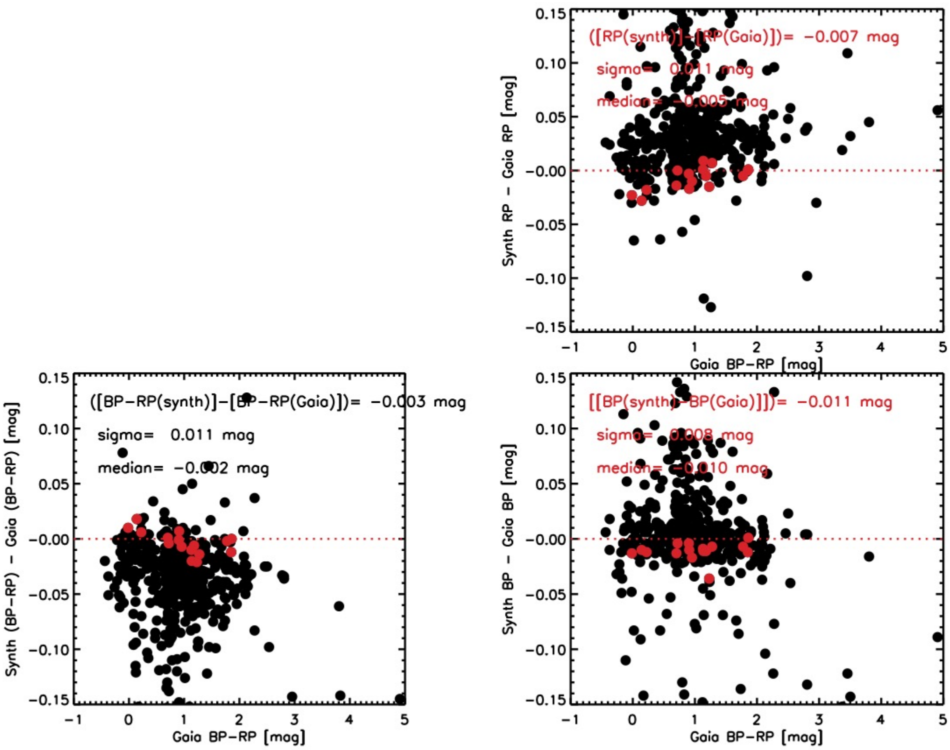

Fig. 6. NGSL library: Synthetic G, BP, and RP magnitudes vs. Gaia DR3 G, BP, and RP magnitudes. Only stars flagged as "OK" are plotted in black. In red are those with average flux deviation between the BP/RP spectra and XSL spectra within 1%.

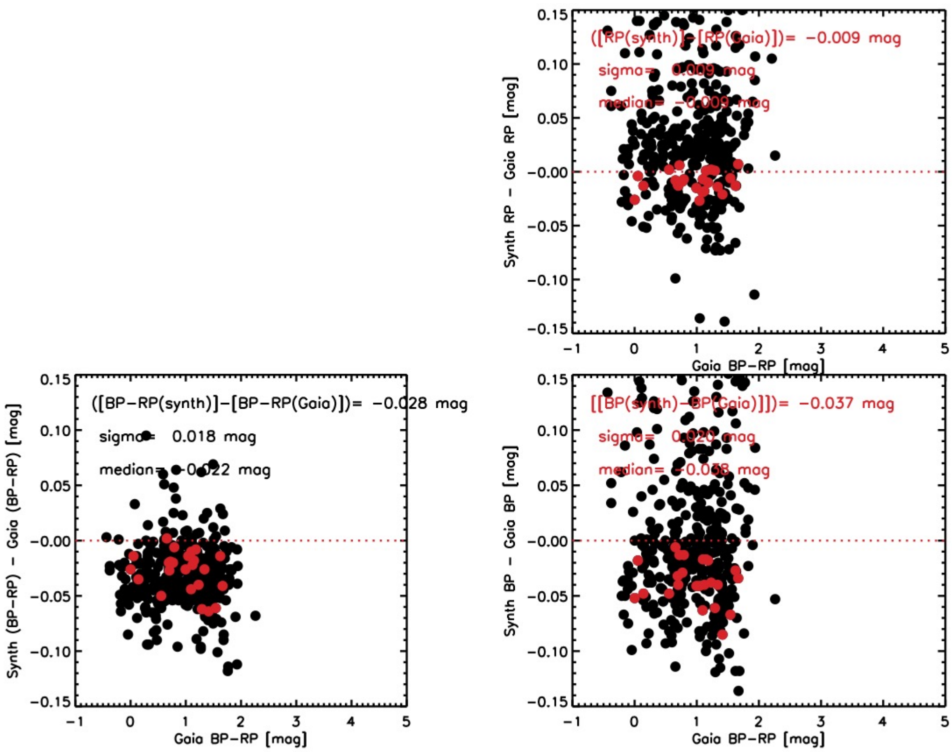

Fig. 7. XSL library: Synthetic G, BP, and RP magnitudes vs. Gaia DR3 G, BP, and RP magnitudes. Only stars flagged as "OK" are plotted in black. In red are those with average flux deviation between the BP/RP spectra and XSL spectra within 1%.

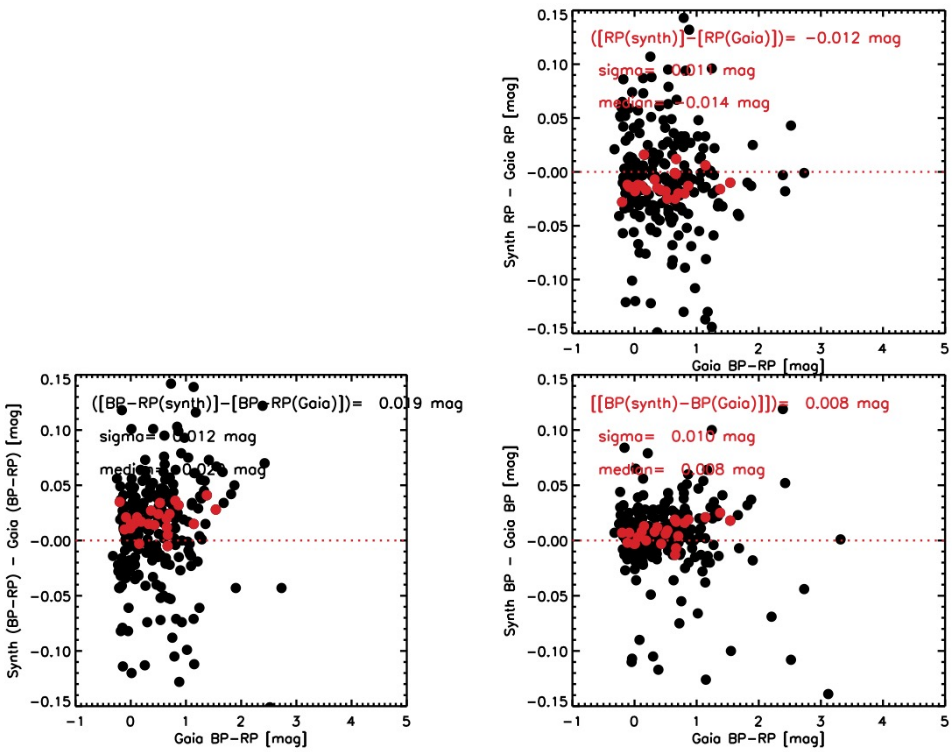

Fig. 8. UVES library: Synthetic G, BP, and RP magnitudes vs. Gaia DR3 G, BP, and RP magnitudes. Only stars flagged as "OK" are plotted in black. In red are those with average flux deviation between the BP/RP spectra and XSL spectra within 1%.