

The Gothard Observatory Synthetic Stellar Photometry Database

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ABSTRACT

Context. To determine stellar luminosities and radii, it is necessary to know the total bolometric fluxes emitted by stars – or equivalently their bolometric corrections (BCs) – as accurately as possible.

Aims. The aim of this paper is to present and describe a new database of synthetic stellar magnitudes and BCs for 752 filters from 78 ground- and space-based instruments calculated using the most recent version of the BOSZ synthetic stellar spectral library.

Methods. From the entire grid of BOSZ theoretical spectra, our synthetic magnitudes in the Vega magnitude system were determined using the corresponding species Python routines.

Results. The database spans effective temperatures from 2800 to 16 000 K, $\log g$ from -0.5 to 5.5 , metallicities from -2.5 to 0.75 , $[\alpha/M]$ from -0.25 to 0.5 , $[C/M]$ from -0.75 to 0.5 , and reddening up to $A_V = 3.1$ mag. Using high-resolution ($R = 50\,000$) synthetic spectra allowed us to precisely track the effects of abundances on stellar BCs and luminosities.

Conclusions. By applying the new BCs to 192 000 APOGEE stars, we calculated luminosities and demonstrated that neglecting carbon can introduce up to $\pm 0.2\%$ errors in luminosity. The new Gothard Observatory Synthetic Stellar Photometry Database may enable more accurate fundamental parameter determinations for large stellar samples using a vast amount of past, present, and upcoming surveys, such as Gaia, LSST, and the Roman Space Telescope.

Key words. techniques: photometric – techniques: spectroscopic – stars: abundances – stars: fundamental parameters

1. Introduction

Synthetic stellar photometry is an essential method and tool for relating theoretical stellar parameters – namely effective temperature (T_{eff}), surface gravity ($\log g$), metallicity ($[M/H]$), and often alpha-element abundances ($[\alpha/M]$) – to observable quantities, such as magnitudes and colors in various photometric systems. To determine stellar luminosities and radii, it is necessary to know the total bolometric fluxes emitted by stars – or equivalently their bolometric corrections (BCs). Recent versions of BCs are usually based on theoretical spectral libraries calculated using stellar atmosphere models and atomic and molecular line lists.

Casagrande & VandenBerg (2014) provided an overview of synthetic photometry and also included the case of 2MASS, SDSS, HST, and Johnson-Cousins filters, while Casagrande & VandenBerg (2018b) discussed in detail the application of synthetic photometry using MARCS stellar atmosphere models based on the solar chemical composition of Grevesse et al. (2007). These studies determined synthetic colors, BCs, and reddening coefficients for the Hipparcos/Tycho, Pan-STARRS1 (Chambers et al. 2019), SkyMapper (Keller et al. 2007), and JWST photometric systems (85 filters in total). Using absolute spectrophotometry from the CALSPEC library (Bohlin et al. 2014), they showed that bolometric fluxes can be recovered to about 2 percent from BCs in a single band.

Expanding their previous work, a similar study was carried out by Casagrande & VandenBerg (2018a) for the Gaia (Gaia Collaboration 2016) G_{BP} , G , and G_{RP} bands based on Gaia data release 2 (DR2) (Gaia Collaboration 2018) and also the entire grid of the MARCS models. They investigated the effects of slightly different transmission curves (“processed” and “revised”) and found differences typically at a few millimagnitudes, along with a magnitude-dependent offset in Gaia G magnitudes. They concluded that the G and G_{RP} magnitudes are typically better than the G_{BP} magnitude in recovering bolometric fluxes¹.

Chen et al. (2019) presented the YBC database of stellar BCs, in which they homogenized widely used theoretical stellar spectral libraries and provided BCs for many (at least 70) popular photometric systems, including Gaia (DR2) filters. They computed BC tables both with and without extinction; therefore, the YBC database provides a more realistic way to fit isochrones with spectral-type dependent extinction. The effect of accounting for reddening in the BC is very clearly seen in their Fig. 4, which shows a ~ 0.2 mag difference in the Gaia G band, ~ 0.1 mag in the Gaia $G_{\text{BP}}-G_{\text{RP}}$ color, and ~ 1 mag in the HST/WFC3 F218W filter at $A_V = 0.5$ mag. Therefore, they suggested using extinction coefficients dependent on spectral type for Gaia filters and UV filters whenever $A_V \gtrsim 0.5$ mag.

¹ An updated version of their BC database for Gaia DR3 is available on L. Casagrande’s GitHub page. See <https://github.com/casaluca/bolometric-corrections>

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The only database of BCs to Gaia G magnitudes for Gaia data release 3 (DR3) (Gaia Collaboration 2023) was published by Creevey et al. (2023). They provided a Python-implemented BC function that takes as input the effective temperature T_{eff} , surface gravity $\log g$, iron abundance $[\text{Fe}/\text{H}]$, and alpha-enhancement $[\alpha/\text{Fe}]$, and returns the model value BC_G for that combination of parameters. The BC_G values for interpolation were derived from synthetic stellar spectra based on a grid of MARCS models (Gustafsson et al. 2008), supplemented with intermediate-temperature stars (Shulyak et al. 2005), as a function of T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$. They assumed $[\alpha/\text{Fe}] = 0.0$ when calculating the correction for all stars because $[\alpha/\text{Fe}]$ was only estimated for a small fraction of the sources. Their adopted value for the BC for the Sun is $\text{BC}_{G,\odot} = +0.08$ mag, where $M_{\text{bol},\odot} = 4.74$ yields an absolute magnitude of the Sun $M_{G,\odot} = 4.66$ mag. For extinction calculations they used the wavelength-dependent extinction law by Fitzpatrick (1999).

In this work, we used the BOSZ synthetic spectral library – originally developed to flux calibrate the James Webb Space Telescope (Mészáros et al. 2024) – to compute new magnitudes and BCs for 752 filters from 78 instruments used in 35 facilities. We calculated new luminosities for about 192 000 APOGEE stars for the Gaia DR3 G filter. The paper is structured as follows. We summarize the calculation methods, including the scope of the database in Section 2, followed by the validation aspects of our database in Section 3. Next, we compare our new Gaia G BCs with the set of official Gaia DR3 G values in Section 4, while in Section 5 we present our new luminosity values for a large sample of APOGEE stars. Finally, we provide a brief overview of our results in Section 6.

2. Calculation methods

Synthetic photometry is the process of deriving brightness and color values by convolving fluxes from stellar atmospheric models with filter functions of standard photometric passbands. The response function of a standard photometric system is usually obtained by multiplying the function describing the reflectivity of the telescope mirror by the transfer function of the filters and camera optical system and the quantum efficiency of the detector as a function of wavelength. For ground-based observations, this must be multiplied by the transfer function of the Earth's atmosphere for an air mass of at least 1.0. Atmospheric correction is usually performed in the broad UV bands (such as the U band), where extinction is large and varies significantly within the band; in the red edge of the optical range; and in the IR bands, where absorption by molecules (e.g., H_2O and O_2) is significant. Previous summaries of synthetic photometry methods appear in Cousins (1976), Buser (1986), Straizys (1996), and Cohen et al. (1996), while a pedagogical introduction to the main concepts has more recently appeared in Casagrande & VandenBerg (2014).

2.1. From fluxes to magnitudes

In its most common and simplest form, synthetic magnitude is proportional to the logarithm of

$$\frac{\int_{x_a}^{x_b} f_x T_\zeta dx}{\int_{x_a}^{x_b} T_\zeta dx}, \quad (1)$$

where f_x denotes the flux at x , T_ζ represents the system response function, and the integration over x is carried out in the wavelength ($x = \lambda$) or frequency ($x = \nu$) space between the limits

x_a and x_b . The system response function T_ζ represents the total throughput, affected by everything between the top of the Earth's atmosphere and the final detection of the photon. Hence, the proper characterization of T_ζ is a crucial and nontrivial part of most photometric systems.

Although we work with fluxes as physical quantities, in astronomy we use the magnitude scale created by Hipparchos and later formalized by Pogson to characterize the stellar brightness. According to the Pogson formula, stellar brightness through the filter i is

$$m_i = -2.5 \log \frac{\int_{x_a}^{x_b} f_x T_\zeta dx}{\int_{x_a}^{x_b} f_x^0 T_\zeta dx} + m_{i,0}, \quad (2)$$

where f_x^0 and $m_{i,0}$ are the flux and magnitude values of a standard star (or reference spectrum), respectively, and $\log$ is the logarithm with base 10.

Since the flux is determined after the source signal has been recorded by the detector, a distinction must be made between photon-counting and energy-integrating detectors. The CCD (charge-coupled device) cameras used today almost exclusively count the photons arriving at the detector surface per unit time; thus, in the formula defining the magnitude, it is useful to divide the flux f_λ by the photon energy $h\nu = hc/\lambda$. Without going into details, this means that, in the formulas, we must replace T_ζ by λT_ζ . (The hc constant disappears due to normalization over T_ζ .) So, if we use the wavelength, stellar brightness is defined as

$$m_i = -2.5 \log \frac{\int_{\lambda_1}^{\lambda_2} \lambda f_\lambda T_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} \lambda f_\lambda^0 T_{\lambda,i} d\lambda} + m_{i,0}. \quad (3)$$

Depending on the flux of the reference star or the spectra f_λ^0 (f_ν^0), the most widely used magnitude systems are the following:

- *Vega magnitude system*. The spectrum of Vega (α Lyr) is used as a reference spectrum. The reference magnitudes are set so that Vega has a magnitude equal to or slightly different from zero. The latest Vega spectrum is available in the CALSPEC² database (Bohlin et al. 2014).
- *AB magnitude system* (Oke 1974). The reference spectrum of the AB magnitude system has a constant value of $f_\nu^0 = 3.63 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$. The reference magnitudes are therefore set to $-2.5 \log f_\nu^0 = -48.6$ mag.
- *ST magnitude system* (STScI Development Team 2018). The reference spectrum of the ST magnitude system has a constant value of $f_\lambda^0 = 3.63 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. The reference magnitudes are therefore set to $-2.5 \log f_\lambda^0 = -21.1$ mag.

Note that in the AB system, where frequency is used instead of wavelength, $f_\lambda^{(0)} d\lambda$ should not simply be replaced with $f_\nu^{(0)} d\nu$ but with $-f_\nu^{(0)} \frac{c}{\nu^2} d\nu$.

2.2. Bolometric corrections

Synthetic spectral libraries provide the stellar flux F_λ (usually in erg per second per square centimeter per angstrom) on a surface element for a given set of stellar parameters. The flux F_λ is related to the effective temperature T_{eff} of the star through the form

$$F_{\text{bol}} = \int_0^\infty F_\lambda d\lambda = \sigma T_{\text{eff}}^4, \quad (4)$$

² https://ssb.stsci.edu/cdbs/calspec/alpha_lyr_stis_011.fits

where σ is the Boltzmann constant. If the distance to the star from Earth is d , then the flux can be measured by

$$f_{\lambda,d} = \left(\frac{R}{d}\right)^2 F_{\lambda} 10^{-0.4A_{\lambda}}, \quad (5)$$

where A_{λ} denotes the extinction between the star and the observer. If distance d is chosen to be 10 pc, the absolute magnitude M_i for a photon-counting photometric system is

$$\begin{aligned} M_i &= -2.5 \log \frac{\int_{\lambda_1}^{\lambda_2} \lambda f_{\lambda,10\text{pc}} T_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} \lambda f_{\lambda}^0 T_{\lambda,i} d\lambda} + m_{i,0}, \\ &= -2.5 \log \left[\left(\frac{R}{10\text{pc}}\right)^2 \frac{\int_{\lambda_1}^{\lambda_2} \lambda F_{\lambda} 10^{-0.4A_{\lambda}} T_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} \lambda f_{\lambda}^0 T_{\lambda,i} d\lambda} \right] + m_{i,0}. \end{aligned} \quad (6)$$

The definition of bolometric magnitude M_{bol} is

$$\begin{aligned} M_{\text{bol}} &= M_{\text{bol},\odot} - 2.5 \log(L/L_{\odot}), \\ &= M_{\text{bol},\odot} - 2.5 \log(4\pi R^2 F_{\text{bol}}/L_{\odot}). \end{aligned} \quad (7)$$

According to the IAU 2015 resolution (Mamajek et al. 2015), the absolute bolometric magnitude for a nominal solar luminosity of 3.828×10^{26} W is $M_{\text{bol},\odot} = 4.74$ mag.

Given an absolute magnitude M_i in the filter band i for a star of absolute bolometric magnitude M_{bol} , the BC_{*i*} is

$$\text{BC}_i = M_{\text{bol}} - M_i = m_{\text{bol}} - m_i. \quad (8)$$

The bolometric flux of a star with observed magnitude m_i and BC_{*i*} is given by

$$f_{\text{bol}} = \frac{\pi L_{\odot}}{(1.296 \times 10^7 \text{ au})^2} 10^{-0.4(\text{BC}_i - M_{\text{bol},\odot} + m_i)}. \quad (9)$$

This equation is equivalent to that of Casagrande & Vandenberg (2018b). The solar luminosity and the astronomical unit should be given in erg per second and centimeter, respectively. The adopted value for au from IAU Resolution B2 is $\text{au} = 1.495978707 \times 10^{13}$ cm.

The new BOSZ synthetic spectral library provides surface brightness values (H) erg per second per square centimeter per angstrom, which can be converted to the flux in the proper format given in watts per square meter using the equation

$$f = 10 \times 4\pi H \left(\frac{R_{\odot}}{1\text{ au}}\right)^2. \quad (10)$$

Once we obtain the flux from the synthetic spectrum, we calculate the BC using Eq. (9) as

$$\text{BC}_i = -2.5 \log_{10} \frac{f_{\text{bol}}}{3.1993 \times 10^{-11}} - m_i + 4.74, \quad (11)$$

where 3.1993×10^{-11} is the numerical value of the expression containing π , $L_{\odot}$, and au. All BCs presented in this paper were calculated using Equation (11). Now, taking into account interstellar reddening, the absolute bolometric magnitude can be determined as

$$M_{\text{bol}} = m_i + \text{BC}_i + 5 - 5 \log d - A_i, \quad (12)$$

where d is the distance to the star in parsecs and A_i is the interstellar extinction. Given the absolute bolometric magnitude, the

luminosity of a star can be calculated in a straightforward way using the following equation:

$$\frac{L}{L_{\odot}} = 10^{(M_{\text{bol},\odot} - M_{\text{bol}})/2.5}. \quad (13)$$

Knowing the luminosity, the stellar radius can be determined from the Stefan-Boltzmann law as

$$\frac{R}{R_{\odot}} = \sqrt{\frac{L}{L_{\odot}} \frac{T_{\text{eff},\odot}^2}{T_{\text{eff}}^2}}. \quad (14)$$

2.3. Parameters of the new BC database

Our new BC calculations are based on the BOSZ synthetic spectral library (Bohlin et al. 2017; Mészáros et al. 2024), which was developed to flux calibrate the James Webb Space Telescope. Mészáros et al. (2024) gives a detailed description of the updated version used for all calculations presented in this paper.

The new grid was calculated with synspec (Hubeny et al. 2021) using the LTE approximation and covers metallicities [M/H] from -2.5 to 0.75 dex, $[\alpha/\text{Fe}]$ from -0.25 to 0.5 dex, and [C/M] from -0.75 to 0.5 dex, providing synthetic spectra for 336 unique compositions. Calculations for stars between 2800 and 8000 K use MARCS model atmospheres (Gustafsson et al. 2008), and ATLAS9 (Kurucz 1979; Mészáros et al. 2012) is used between 7500 and 16 000 K. Examples of BCs in selected filters are shown in Fig. 1.

The new BOSZ grid includes 628 620 synthetic spectra from 50 nm to 32 μm with models for 495 T_{eff} -log g parameter pairs per composition and per micro-turbulent velocity. Each spectrum is available in eight different resolutions spanning $R = 500$ to 50 000, as well as the original synthesis resolution. The micro-turbulent velocities are 0, 1, 2, and 4 km s^{-1} . In this paper, the $R = 50\,000$ spectra with a 2 km s^{-1} micro-turbulent velocity were selected for all model spectra. To carefully test the effects of carbon and α -abundances on synthetic magnitudes and BCs, we derived these values using spectra at various resolutions (5000, 10 000, 20 000, and 50 000) from the BOSZ database. We concluded that, despite the small magnitude differences across resolutions, spectra at $R = 50\,000$ best tracked the effects of α and carbon abundances.

In the 2024 version of the BOSZ grid, significant updates were made to the molecular line list by including line lists from the ExoMol project (Tennyson & Yurchenko 2012; Tennyson et al. 2016). The new BOSZ grid includes 23 molecules (AlH, AlO, C₂, CaH, CaO, CH, CN, CO, CrH, FeH, H₂, H₂O, MgH, MgO, NaH, NH, OH, OH⁺, SiH, SiO, TiH, TiO, and VO). Several molecular line lists from the previous version have been updated, with newer line lists contain more lines – mainly in the infrared region – enabling more accurate spectral modeling. In principle, more accurate synthetic magnitudes and BCs can be calculated from higher-quality synthetic spectra.

2.4. Fixes made in the 2024 version of the BOSZ grid

During the calculation of the Gothard Observatory Synthetic Stellar Photometry Database, the team discovered issues with the 2024 version of the BOSZ grid, which have since been fixed and incorporated into the BOSZ website³. One issue was relatively minor: an eight-level H atom originally used led to a lack of higher-level H lines above 5.8 microns. To fix the issue,

³ <https://archive.stsci.edu/hlsp/bosz>

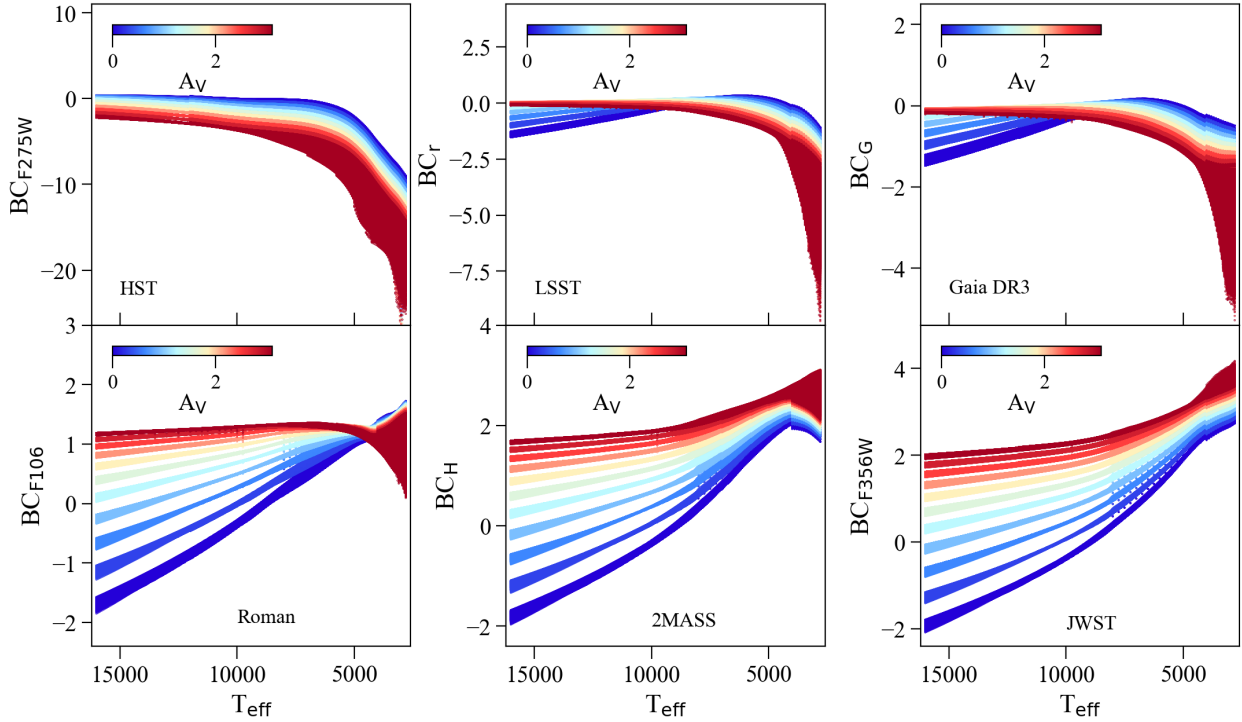


Fig. 1. Examples BC dependence on effective temperature in selected HST, LSST, Gaia, Roman, 2MASS, and JWST filters. Filters are ordered by increasing central wavelength. The BCs are color-coded by reddening.

we used a 40-level H atom, which enabled the correct calculation of all hydrogen lines up to 32 microns. The second issue involved OH+. The 2024 version incorrectly used the OH partition table for OH+, resulting in stronger-than-expected molecular absorption lines between 300 and 450 nm and 1 and 8 microns for models below 6500K. This issue has also been fixed in the code, providing correct OH+ line strengths. All BCs and synthetic magnitudes presented in this paper are based on fixed 2024 BOSZ spectra.

2.5. Interstellar reddening

Interstellar reddening was also taken into account when determining BCs. We used the `ccm89` reddening function of the `extinction` Python package⁴. This function uses the reddening law determined by Cardelli et al. (1989). After carrying out several numerical tests, we decided not to redden the BCs but rather to redden the synthetic spectra themselves before determining the BCs. Reddening the spectra was achieved by varying A_V between 0.0 and 3.1 in 11 steps with a step size of 0.31 in equation $R_V = A_V/E(B - V)$, where R_V was set to 3.1. This resulted in a 0.1 size in $E(B - V)$ between $E(B - V) = 0$ and 1.

2.6. Program package species

From the BOSZ theoretical spectra, our synthetic magnitudes in the Vega magnitude system were determined using the corresponding `species` Python package routines⁵ (Stolker et al. 2020). The `species` software package can use the Spanish Virtual Observatory (SVO) filter profile service⁶ to retrieve the transmission functions for filters used in instruments of many

ground-based observatories and space telescopes. `species` can automatically choose between the AB and Vega photometric systems. The latter choice can be forced by using the spectrum of Vega. In this case `species` gives the magnitude values relative to Vega under the assumption that Vega's brightness is 0.03 mag in all filters by default. While this is mostly true for BVRI filters, it may not be the case for other systems. The zero point depends on the absolute flux used to standardize those systems. This is important to point out, because `species` does not account for the offsets between systems; therefore, the published magnitudes and BCs may have systematic discrepancies relative to the specific photometric system definitions in the range of a few hundredths of magnitudes in certain filters. At the start of the calculation, it downloads the most recent spectrum of Vega from the CALSPEC database (Bohlin et al. 2014) and calculates the magnitudes for the synthetic spectra using those derived from that. The Vega spectrum used in this paper is `alpha_lyr_stis_011.fits`, which can be downloaded from the CALSPEC⁷ database.

3. The scope of the database

The Spanish Virtual Observatory Filter Profile Service (SVO FPS, Rodrigo et al. 2012; Rodrigo & Solano 2020) provides standardized information, including transmission curves and calibration, on more than 7900 astronomical filters. The service is designed to be compliant with the Virtual Observatory Photometry Data Model, and all the information is provided through both a web portal and VO services, enabling other services and applications to access relevant filter properties in a simple way.

⁴ <http://github.com/kbarbary/extinction>

⁵ <https://species.readthedocs.io/en/latest/index.html>

⁶ <http://svo2.cab.inta-csic.es/theory/fps>

⁷ https://ssb.stsci.edu/cds/calspec/alpha_lyr_stis_011.fits

Table 1. List of facilities, instruments, and number of filters used in BC and synthetic magnitude calculations, following the SVO website naming convention.

Facility	Instrument	N	Facility	Instrument	N
2MASS	2MASS	3	KPNO	DESI	3
AKARI	IRC	9		TIFKAM	4
APO	Broad	5	LaSilla	WFI	23
	SDSS	5	LBT	LBCB	7
CAHA	Omega2000	15		LBCR	13
CASTOR	CASTOR0	2	LCO	OGLE-IV	2
CFHT	MegaCam	12		WFCCD	4
	Wircam	11	LSST	LSST	6
Euclid	NISP	3	NOT	NOTcam	16
	VIS	1	Palomar	Arp1961	4
GAIA	GAIA2r	3		GSC2	3
	GAIA3	4		POSS	2
GALEX	GALEX	1		Wevers1986	3
Gemini	DSSI	4		ZTF	3
	GSAOI	20	PAN-STARRS	PS1	7
	Michelle	8	Paranal	ISAAC	9
Generic	Bessell	5		OmegaCAM	24
	Bessell_JHKLM	6		VISTA	5
	Cousins	2	Roman	WFI	10
	Johnson	7	SkyMapper	SkyMapper	6
	Stromgren	4	SLOAN	SDSS	5
GTC	CanariCam	18	Spitzer	IRAC	4
	OSIRIS	30		IRS	2
Hipparcos	Hipparcos	3		MIPS	1
HST	ACS_HRC	18	Subaru	CIAO	17
	ACS_WFC	13		FOCAS	5
	NICMOS1	11		HSC	5
	NICMOS2	17		IRCS	6
	NICMOS3	12		MOIRCS	5
	WFC3_IR	13		OHS	9
	WFC3_UVIS1	28		Suprime	26
	WFC3_UVIS2	28	TYCHO	TYCHO	6
	WFPC2-PC	24	UKIRT	UKIDSS	5
	WFPC2-WF	26		WFCAM	5
IRAS	IRAS	2	WHT	INGRID	13
JWST	MIRI	9		LRIS	13
	NIRCam	29		PAUCam	6
	NIRISS	12		PFIP	2
Keck	ESI	3	WISE	WISE	4
	LRIS	11			
	LWS	11			
	NIRC2	11			

We carefully checked the SVO FPS and selected the facility/instrument pairs considered most important for modern astronomical photometry. Our sample contains a total of 752 filters for 78 instruments from 35 ground-based observatories and space telescopes. From the available filter transmission curves, we selected only those with labels indicating use for full-fledged photometric measurements. The facilities, instruments, and the number of filters are listed in Table 1. All filters selected had a minimum wavelength exceeding 50 nm and a maximum wavelength below 32 microns in order to align with the wavelength range covered by the BOSZ spectra.

The parameter space covered by our BC database is almost the same as that of the BOSZ spectral library. The main difference is that in the spectral library the step size of T_{eff} is 100 K

Table 2. List of grid parameters used for magnitude and BC calculations.

Grid parameter	Lower boundary	Upper boundary	Step size
T_{eff} (K)	2800	16 000	50
$\log g$	-0.50	5.50	0.50
[M/H]	-2.50	0.75	0.25
[α /Fe]	-0.25	0.50	0.25
[C/M]	-0.75	0.50	0.25
A_V	0.00	3.10	0.31

Table 3. Synthetic magnitudes and BCs of the Sun following the SVO website naming convention.

Filter ID	Absolute magnitude	Bolometric correction
2MASS/2MASS.H	3.3655	1.3931
2MASS/2MASS.J	3.6792	1.0504
2MASS/2MASS.Ks	3.3024	1.4272
AKARI/IRC.L15	3.2689	1.4607
AKARI/IRC.L18W	3.2670	1.4626

below 4000 K, 250 K between 4000 and 12 000 K, and 500 K above 12 000 K, while in our BC database it is 50 K throughout the temperature range. The magnitude and BC values on the denser grid points were determined by a third-order spline interpolation. Due to potentially large flux differences between model spectra, we did not interpolate the spectra themselves to determine the magnitude and BC values for the 50 K step interval. Rather, we performed the interpolation using the calculated magnitude and BC values at the original grid points. No interpolation was performed for the other parameters ($\log g$, [α /M], [C/M], and A_V). The parameters of the final grid are listed in Table 2. The Sun BCs and synthetic magnitudes for all filters can be found in Table 3.

3.1. Validation of color-color relationships

To check the accuracy of our synthetic magnitude scale, we compared the observed Gaia–2MASS (Skrutskie et al. 2006) color relationship data with the same colors in our database. The observed and modeled Gaia and 2MASS color indices $G_{\text{BP}}-G_{\text{RP}}$ and $J-K_s$ are plotted as a function of all relevant physical parameters (T_{eff} , $\log g$, [M/H], [α /M], [C/M], and A_V) in Fig. 2. We selected nearly two million common stars from the Gaia DR3 and 2MASS databases, which are plotted with contour lines in Fig. 2. To generate the contours, we used only those stars with magnitudes brighter than 12 in the G filter, errors in G , G_{BP} , and G_{RP} magnitudes less than 0.01, errors in J , H , and K_s magnitudes less than 0.03, and parallax errors less than 10%. The filtering conditions for errors in brightness values are based on the relationships given by Carrasco⁸ for Gaia DR2. As a result of the cuts, 1 984 111 Gaia–2MASS stars were included in the sample, from which the contour lines were drawn on the color-color diagrams. We did not filter for interstellar reddening as the

⁸ https://gea.esac.esa.int/archive/documentation/GDR2/Data_processing/chap_cu5pho/sec_cu5pho_calibr/ssec_cu5pho_PhotTransf.html

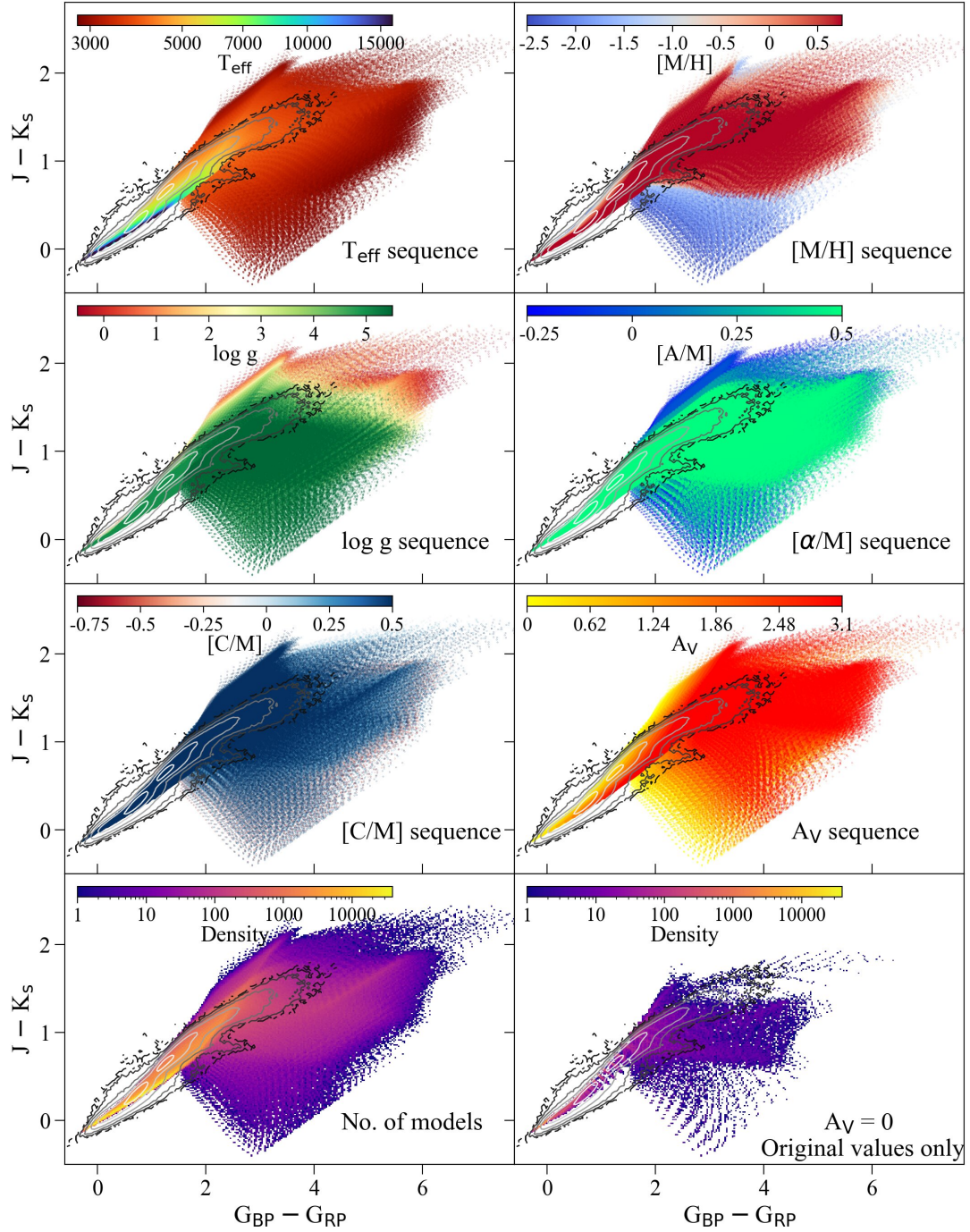


Fig. 2. $J - K_s$ vs. $G_{BP} - G_{RP}$ color-color diagram. The contoured area represents stars observed by both Gaia and 2MASS (see Section 3.1 for further details). Each panel is color-coded by a different parameter indicated in the panels themselves.

synthetic color indices for all reddening values are plotted in the figure.

Overall, the agreement between the synthetic and the observed colors is very good; however, there are regions in the color space where the synthetic colors do not match the observation. One such region comprises high-temperature stars where either the $G_{BP} - G_{RP}$ color is too red, or the $J - K_s$ color is too blue (or the combination of the two) compared to the color derived from the observations. This discrepancy, nevertheless, is small. The reason behind this discrepancy is currently unknown. The distribution of the synthetic color points forms a “fan” shape much wider than the observation if $G_{BP} - G_{RP} > 1.5$, where the

temperature is lower than 5000–7000 K, while the colors have a narrow distribution if $G_{BP} - G_{RP} < 1.5$ (the temperature panel of Fig. 2). This occurs because at temperatures higher than 7000 K the rest of the main atmospheric parameters have a much weaker effect on the stellar spectra than at lower temperatures.

The majority of the observed stars are main-sequence stars with solar metallicities (lower branch of the contour lines) and giant stars (upper branch of the contour lines), as seen in the $\log g$ panel of Fig. 2. Because the Gaia-2MASS sample is restricted in brightness, the sample does not contain stars with $G_{BP} - G_{RP} > 4$, which are the very low-temperature main-sequence and giant stars. The data points at the bottom of the fan, shown with

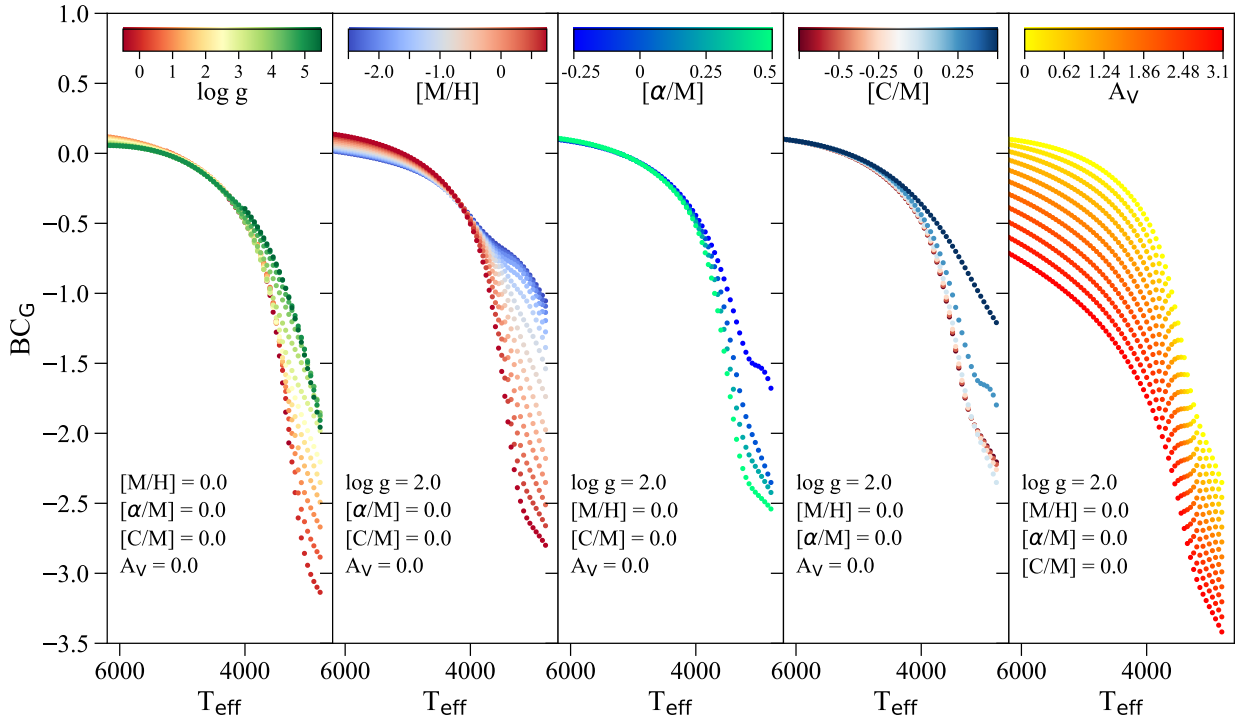


Fig. 3. Effects of various parameters on Gaia DR3 BC_G . The fixed parameters are listed in the panels.

blue points in the metallicity panel, represent the metal-poor red dwarfs, which are not in the observed Gaia-2MASS sample.

Some of the discrepancy between synthetic and observed colors comes from the fact that the BOSZ database includes main atmospheric parameters where there are no observed stars to provide a complete grid. One such region is the most metal-rich and α -poor combination, which can be seen as a narrow strip of dark blue points in the α panel of Fig. 2 between $J - K_s$ 1.5 and 2.2. The reddest, extremely metal-rich ($[M/H] = 0.75$), but non-existing red giants are at $G_{BP} - G_{RP} > 4$ and $J - K_s > 1.5$.

3.2. Effect of grid parameters on the bolometric correction

Fig. 3 shows the effect of the astrophysical parameters $\log g$, $[M/H]$, $[\alpha/M]$, $[C/M]$, and A_V on Gaia DR3 BC_G . In each of the five panels, the values of BC_G are plotted against the effective temperature, which varies between 6000 K and 2800 K, and the effects of the other four parameters are indicated by color codes. The fixed parameters are shown in the lower left of the panels in Fig. 3. For $\log g$, the abundance values were set to the solar value of 0.0 dex, while for the abundance panels the $\log g$ value was set to 2.0 dex, i.e., the figure only shows the case of giant stars. In each case, the BC starts from around 0.0 at the higher-temperature end of the range, then decreases sharply around 4500 K and becomes increasingly negative. It is clear that below this temperature, all four atmospheric parameters ($\log g$, $[M/H]$, $[\alpha/M]$, and $[C/M]$) have an effect on the BC, which can even exceed 1.5 magnitudes below 3000 K. In most cases $\log g$ and $[M/H]$ have the strongest effect on the BC, but as the temperature decreases $[\alpha/M]$ and $[C/M]$ become important factors for cool stars.

To date, the effect of carbon on the Gaia DR3 G BC has not been studied. By using the BOSZ database, it became possible to examine how $[C/M]$ values affect the BC. This can be seen in the fourth panel of Fig. 3. While low $[C/M]$ values have little effect

on the BC, values of $[C/M]$ higher than 0–0.25 dex can affect the BC almost as much as or more than the $[\alpha/M]$ dimension. Below 4500 K carbon has a significant effect on the structure of stellar atmospheres, which must be accounted for during model atmosphere calculations, as implemented in the BOSZ grid. Thus, for carbon-enriched stars it is important to address their carbon content when calculating their luminosity and radius.

Interstellar reddening has a significant effect on BCs and should not be ignored, as emphasized for example by Chen et al. (2019). As mentioned above, the spectra themselves were reddened instead of BCs. The effect of reddening between $A_V = 0.0$ and 3.1 on the Gaia DR3 G BC can be seen in the last panel of Fig. 3. Higher reddening significantly decreases the BC, although the correlation between the two parameters is not linear.

4. Comparing Gaia DR3 G bolometric corrections with literature

Here, we discuss the differences in the official Gaia DR3 G BCs (Creevey et al. 2023) and those presented in this paper. The Gaia DR3 BC software tool also used a MARCS model grid from Gustafsson et al. (2008) up to 8000 K (extending to other spectrum libraries above that value; see Table 2 in Creevey et al. (2023)), with a slightly wider range of T_{eff} than our new BOSZ models, from 2500 to 20 000 K. The values of $\log g$ differ only at the upper limit, ranging up to 5.0 for Gaia DR3. Its metallicity range of -5.0 to $+1.5$ is wider than the range of the new BOSZ models; however, the BOSZ models cover a wider range of $[\alpha/M]$ values. In Creevey et al. (2023), the α -element enhancement range spans from 0.0 to $+0.4$. The most significant difference between the two model grids is that the new BOSZ models account for carbon contribution, whereas the Gaia DR3 G BCs do not.

The difference between the Gaia DR3 G BCs and those of Creevey et al. (2023) for the same parameters is shown in

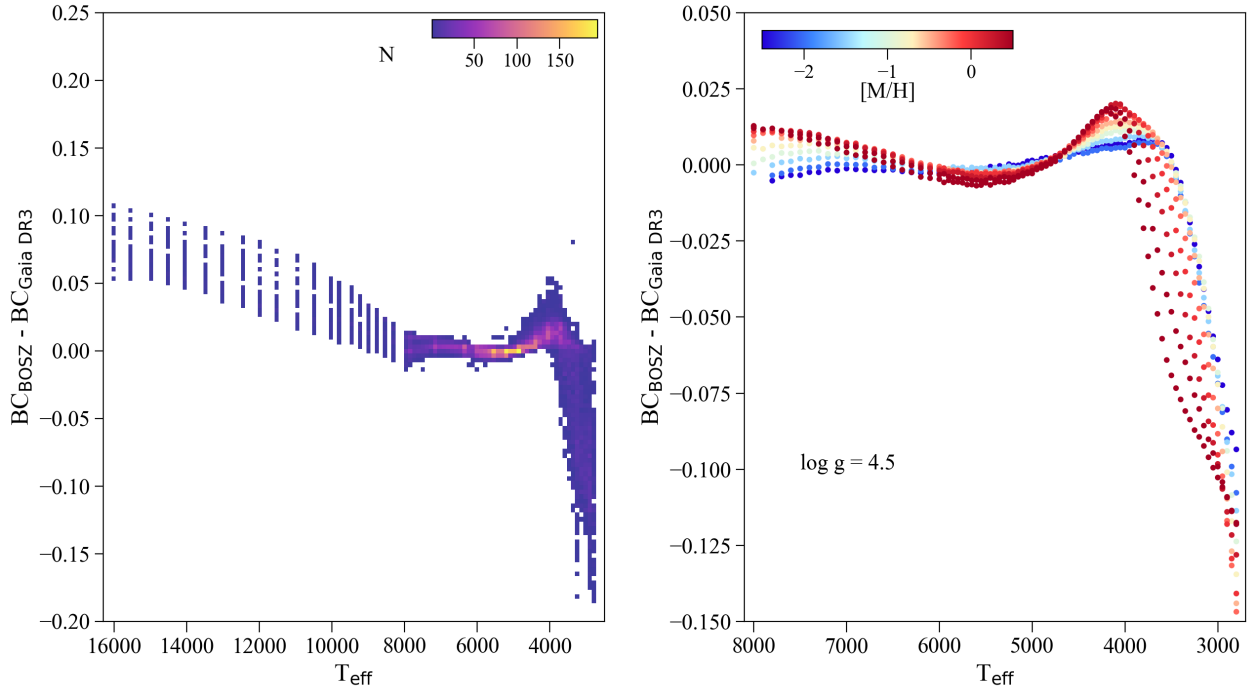


Fig. 4. Difference between the BC_G from this paper and from Gaia DR3 as a function of T_{eff} . Left: all common T_{eff} , $\log g$, and $[M/H]$ combinations. Right: $\log g$ set to 4.5 to reveal the metallicity-dependent differences on the main sequence. $[\alpha/M] = [C/M] = 0.0$ in both cases.

Fig. 4 as a function of T_{eff} . To explore the effects of the updates made on the BOSZ grid compared to the synthetic spectra of Gustafsson et al. (2008), the constant offset of 0.2 applied to Gaia DR3⁹ was removed. Additionally, their adopted value for the Sun's BC is $BC_{G,\odot} = +0.08$ mag, while ours directly comes from the model and is equal to 0.0464 mag (see Table 3). By correcting for this offset as well, the difference seen in Fig. 4 is only due to differences in the synthetic spectral grid used in the calculations.

A large systematic offset that slightly correlates with temperature can be seen for the hot stars above 8000 K. This is probably the result of differing model atmospheres: Gaia DR3 used the line-by-line opacity stellar model atmospheres from Shulyak et al. (2004), while the BOSZ database used ATLAS9 models from Mészáros et al. (2012). The right panel of Fig. 4 shows the $T_{\text{eff}} < 8000$ K range in more detail. Although the agreement between the two BCs is better than 0.02 magnitude in the 8000–4000 K range, significant temperature-dependent systematic offsets can be seen again below 4000 K. This is the temperature regime where molecules dominate the spectrum and the BOSZ grid implements newer, more up-to-date molecular line lists – mostly from the EXOMOL project (Barton et al. 2017a,b) – compared to those available to Gustafsson et al. (2008).

5. APOGEE luminosities

5.1. Our APOGEE sample

To determine new luminosity values for the APOGEE survey (Majewski et al. 2017), we first compiled a list of stars detected by both Gaia DR3 and APOGEE DR17 (Abdurro'uf et al. 2022), then filtered this list according to several criteria. Only APOGEE

⁹ See https://gitlab.oca.eu/ordenovic/gaiadr3_bcg/-/blob/main/gdr3bcg/bcg.py

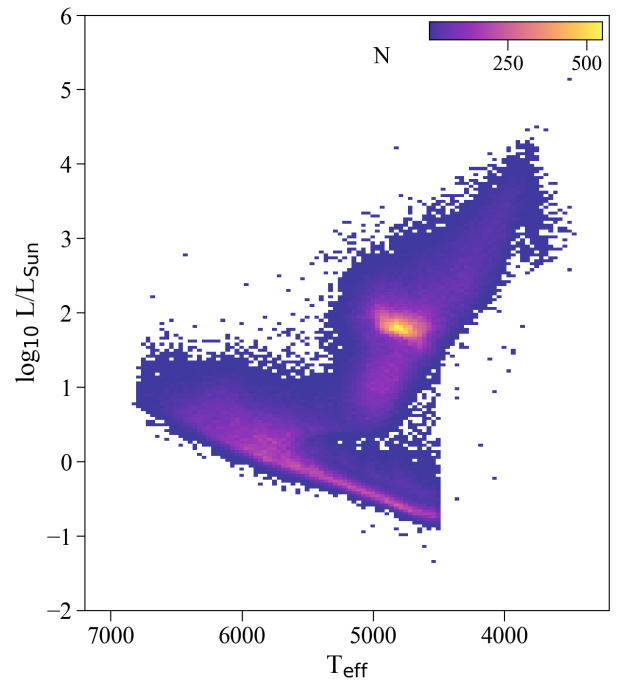


Fig. 5. HRD of our selected APOGEE targets using the new Gaia DR3 BC_G values presented in this paper.

targets without the BAD flag are included in the list. To filter out binaries and pulsating variables, we considered only targets for which the APOGEE parameter v_{scatter} (the scatter of radial velocities derived from spectra taken at different times) is less than 1 km s^{-1} . In addition, we also required that the error in individual radial velocities not exceed 1 km s^{-1} . Finally, we removed targets with a parallax error exceeding 10%. This process resulted in a sample of 192 049 stars.

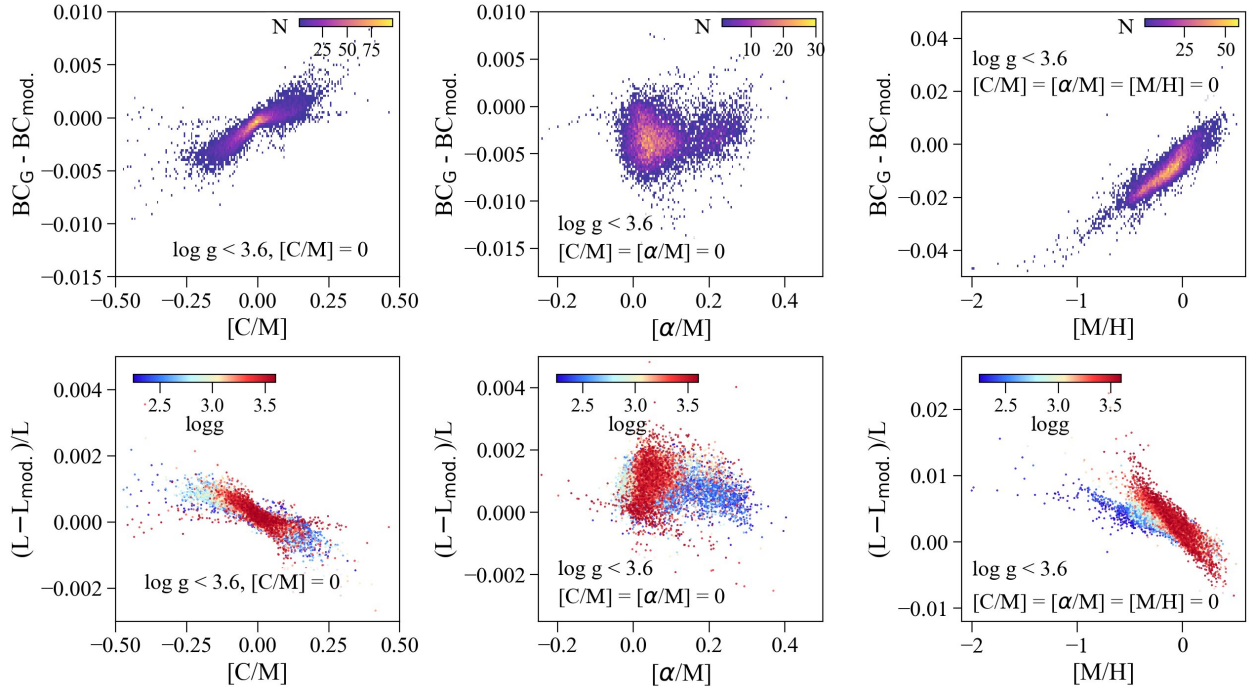


Fig. 6. Error in BC (top panels) and luminosity (bottom panels) caused by fixing carbon, alpha, and metallicity at zero for stars with $\log g < 3.6$. The values BC_G and L were calculated with all three parameters taken into account, and the "mod." (modified) values show the effect when one or several of the parameters – $[M/H]$, $[\alpha/M]$, and $[C/M]$ – are fixed to zero. The value N denotes the number of stars for BC.

After filtering as described above, we applied additional cuts, because α and carbon abundances are unreliable in certain parameter ranges (for more details, see Jönsson et al. 2020; Mészáros et al. 2025). For effective temperatures below 4500 K, only stars with a $\log g$ value less than 3.0 were considered, because carbon abundances of red dwarfs are not reliable. As explored by Mészáros et al. (2025), stars with effective temperatures lower than 4250 K and $[C/M]$ higher than 0.1 also have unreliable abundances; thus, it is necessary to exclude cool, carbon-rich stars from the sample. After cutting, the sample contained 177 728 targets that met the requirements. We note that this sample still contained some metal- and carbon-rich stars above 4250 K, with $[C/M]$ values reaching 0.25 dex.

Fig. 5 shows the new luminosities as functions of the effective temperature for our APOGEE sample calculated using Equations (13) and (14). Here, BC_G values were derived with radial basis function interpolation using the calibrated astrophysical parameters T_{eff} , $\log g$, $[M/H]$, $[\alpha/M]$, raw (uncalibrated) $[C/M]$ and $E(B - V)$ published in APOGEE DR17. Because we excluded the red dwarfs from the sample, a straight vertical boundary is observed at 4500 K, below which only a handful of stars are seen due to probable incorrect luminosity calculations.

5.2. The effect of carbon on bolometric correction and luminosity

Fig. 6 shows the effect on BC (top) and luminosity (bottom) when certain parameters are not account for during BC determination. Only RGB (red-giant branch) stars with $\log g < 3.6$ are selected here to remove erroneous measurements of the abundances in the main sequence. On the vertical axis, the values BC_G and L were calculated with all three parameters taken into account. Moreover, the "mod." (modified) values show the effect when one or several of the parameters – $[M/H]$, $[\alpha/M]$, and

$[C/M]$ – values are fixed to zero. As indicated in the figure, in the first column $[C/M]$ was set to 0.0, but $[M/H]$, and $[\alpha/M]$ were taken from APOGEE; in the second column $[C/M] = [\alpha/M] = 0.0$, but metallicity was allowed to vary; and in the last column, all three parameters were set to zero, meaning only T_{eff} , $\log g$, and the reddening were taken into account.

The effect on BCs is given as a magnitude difference, whereas the effect on luminosities is expressed in relative terms. The histograms are colored by the number of stars. It can be clearly seen that ignoring all three parameters causes errors of up to 0.04 magnitude and up to 1% in BC and luminosity across the full temperature range. We note a clear correlation between the BC difference and the $[M/H]$ value of the star. Of course, the errors decrease once metallicity and α elements are considered. However, if carbon is not used in the BC calculation, at 4500–5000 K – where most of the stars reside – around 0.005 mag and 0.2% error remains in BC and luminosity, respectively. A correlation can be seen between BC differences and $[C/M]$ values when $[\alpha/M]$ and $[M/H]$ are considered but $[C/M]$ is not (top left panel of Fig. 6). These trends are also mirrored in luminosity with opposite signs. This is an expected behavior, because as shown in Section 3.2 the value of BC_G increases with increasing $[C/M]$. Thus, ignoring – as opposed to including – carbon produces lower BC_G values and decreases luminosity.

6. Overview

In this paper, we presented a new, extensive database of synthetic stellar magnitudes and BCs based on the latest BOSZ spectral library. Our goal is to improve estimates of stellar luminosities by delivering accurate BCs across hundreds of photometric filters. In the Gothard Observatory Synthetic Stellar Photometry Database, synthetic magnitudes were computed in the Vega system using the Python package *species*, and BCs were derived

from fundamental flux–magnitude relationships, by applying interstellar reddening directly to the spectra via Cardelli’s extinction law. Covering 752 filters from 78 instruments (ground- and space-based), the database spans effective temperatures from 2800 to 16 000 K, $\log g$ from -0.5 to 5.5 , metallicity from -2.5 to 0.75 , $[\alpha/M]$ from -0.25 to 0.5 , $[C/M]$ from -0.75 to 0.5 , and reddening up to $A_V = 3.1$ mag. Using high-resolution ($R = 50\,000$) synthetic spectra allowed us to precisely track the effect of abundances on the BCs and luminosities of stars.

Validation against nearly two million Gaia–2MASS stars shows strong agreement in color–color space, with minor discrepancies at extreme temperatures. Compared to existing Gaia DR3 BCs, our corrections differ by up to 0.2 mag for hot stars and up to 0.12 mag below 4000 K probably due to the improved treatment of molecular opacities in the BOSZ database. By applying the new BCs to 192 000 APOGEE stars, we calculated refined luminosities and also demonstrated that neglecting carbon or α enhancements can introduce up to 1% errors in luminosity. Overall, the new Gothard Observatory Synthetic Stellar Photometry Database may enable more accurate fundamental parameter determinations for large stellar samples using a vast amount of past, present, and upcoming surveys, such as Gaia, LSST, and the Roman Space Telescope.

Data availability

The full table 3 is available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/706/A318>.

The database can be downloaded in part or in its entirety from <https://gossdpd.gothard.hu/data>.

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