On the use of Gaia magnitudes and new tables of bolometric corrections

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ABSTRACT

The availability of reliable bolometric corrections and reddening estimates, rather than the quality of parallaxes will be one of the main limiting factors in determining the luminosities of a large fraction of Gaia stars. With this goal in mind, we provide Gaia \( G_{\text{BP}}, G \), and \( G_{\text{RP}} \) synthetic photometry for the entire MARCS grid, and test the performance of our synthetic colours and bolometric corrections against space-borne absolute spectrophotometry. We find indication of a magnitude-dependent offset in Gaia DR2 \( G \) magnitudes, which must be taken into account in high accuracy investigations. Our interpolation routines are easily used to derive bolometric corrections at desired stellar parameters, and to explore the dependence of Gaia photometry on \( T_{\text{eff}}, \log g, [\text{Fe/H}], [\alpha/\text{Fe}] \) and \( E(B-V) \). Gaia colours for the Sun and Vega, and \( T_{\text{eff}} \)-dependent extinction coefficients, are also provided.

Key words: techniques: photometric — stars: atmospheres — stars: fundamental parameters — stars: Hertzsprung-Russell and colour-magnitude diagrams

1 INTRODUCTION

Gaia DR2 includes photometry in the \( G_{\text{BP}}, G \), and \( G_{\text{RP}} \) bands for approximately 1.5 billion sources. Its exquisite quality will define the new standard in the years to come, and have a tremendous impact on various areas of astronomy. The first goal of this letter is to lay out the formalism to generate Gaia magnitudes from stellar fluxes, using the official Gaia zero-points and transmission curves (Evans et al. 2018). In doing so, we discuss in some detail the effect of different zero-points, and search for an independent validation of the results using space-based spectrophotometry.

One of the important prerequisites for stellar studies is the availability of Gaia colour transformations and bolometric corrections (BCs) to transpose theoretical stellar models onto the observational plane, and to estimate photometric stellar parameters, including luminosities. In Casagrande & VandenBerg (2014, 2018) hereafter Paper I and II we have initiated an effort to provide reliable synthetic colours and BCs from the MARCS library of theoretical stellar fluxes (Gustafsson et al. 2008) for different combinations of \( T_{\text{eff}}, \log g, [\text{Fe/H}], [\alpha/\text{Fe}] \) and \( E(B-V) \). Here, we extend that work to include the Gaia system. We also provide extinction coefficients and colours for Vega and the Sun, both being important calibration points for a wide range of stellar, Galactic, and extragalactic astronomy.

2 THE GAIA SYSTEM

The precision of Gaia photometry is better than that of any other currently available large catalogs of photometric standards; hence its calibration is achieved via an internal, self-calibrating method (Carrasco et al. 2016). This robust, internal photometric system is then tied to the Vega system by means of an external calibration process that uses a set of well observed spectro-photometric standard stars (Pancino et al. 2012; Altavilla et al. 2015). Observationally, a Gaia magnitude is defined as:

\[
m_\xi = -2.5 \log I_\xi + ZP_\xi
\]

where \( I_\xi \) is the weighted mean flux in a given band \( \xi \) (i.e., \( G_{\text{BP}}, G \), or \( G_{\text{RP}} \)), and \( ZP_\xi \) is the zero-point to pass from instrumental to observed magnitudes (Carrasco et al. 2016). Zero-points are provided to standardize Gaia observations to the Vega (\( ZP_{\text{VEGA}} \) or AB (\( ZP_{\text{AB}} \) systems. The weighted mean flux measured by Gaia for a spectrum \( f_\lambda \) can be calculated from:

\[
I_\xi = \frac{P_s}{10^9hc} \int A_\xi T_\xi d\lambda
\]

where \( P_s \) is the telescope pupil area, \( T_\xi \) the bandpass, \( h \) the Planck constant, and \( c \) the speed of light in vacuum (see Evans et al. 2018 for the units of measure in each term). While \( T_\xi, ZP_{\text{VEGA}} \) and \( ZP_{\text{AB}} \) are the quantities used to process and publish the Gaia DR2 photometry, Evans et al. (2018) also provide a revised set of transmission curves and zero-points (\( T_{\text{rev}}^R, ZP_{\text{REV}}^R \) and \( ZP_{\text{REV}}^R \)). Here, we have generated synthetic photometry using both sets, and call them “processed” (Gaia-pro) and “revised” (Gaia-rev). Although the
revised transmission curves and zero-points provide a better characterization of the satellite system, DR2 magnitudes were not derived using them. To account for this inconsistency, the published DR2 Vega magnitudes should be shifted by $-ZP_{\text{VEGA}} + ZP_{\text{VEGA}}^R$ (Gaia Collaboration et al. 2018). Since many users might overlook this minor correction (at the mmag level), we supply a third set of synthetic magnitudes that take it into account, by using $ZP_{\text{VEGA}}$ in Eq. (1) and $T_\text{ZP}$ in Eq. (2). We call these magnitudes Gaia-DR2 in our interpolation routines, and they should be preferred when comparing predicted colors with published DR2 photometry as is.

While we adopt the formalism of Eq. (1) and (2), we remark that from the definition of AB magnitudes (e.g., Paper I, where $m_{\text{AB}}$ indicates whether $T_\text{C}$ or $T_\text{ZP}$ are used to compute AB magnitudes), an alternative formulation to generate synthetic Gaia magnitudes in the Vega system would be $m_{\text{AB}} + ZP_{\text{VEGA}} - ZP_{\text{AB}}$ (Gaia-pro), $m_{\text{AB}}^R + ZP_{\text{VEGA}}^R - ZP_{\text{AB}}$ (Gaia-rev) and $m_{\text{AB}}^R + ZP_{\text{VEGA}}^R - ZP_{\text{AB}}^R$ (Gaia-DR2). These hold true if the Gaia zero-points in Eq. (1) provide exact standardization to the AB system. We verified that the magnitudes obtained with this alternative formulation vs. Eq. (1) and (2) are identical to < 1 mmag for Gaia-pro, and to 3 mmag for Gaia-rev and Gaia-DR2. Importantly, we note that, in no instance, have we used Gaia DR1 data, nor the pre-launch filter curves (Jordi et al. 2010) anywhere in this paper.

2.1 Check on zero-points

The CALSPEC$^1$ library contains composite stellar spectra that are flux standards in the HST system. The latter is based on three hot, pure hydrogen white dwarf standards normalised to the absolute flux of Vega at 5556 Å. The absolute flux calibrations of CALSPEC stars are regularly updated and improved, arguably providing the best spectrophotometry set available to date, with a flux accuracy at the (few) percent level (Bohlin 2014). In particular, the highest quality measurements in CALSPEC are obtained by the STIS (0.17–1.01μm) and NICMOS (1.01–2.49μm) instruments on board the HST.

By replacing $f_j$ in Eq. (2) with CALSPEC fluxes, it is thus possible to compute the expected $G_{\text{BP}}$, $G$, and $G_{\text{RP}}$ magnitudes for these stars, to compare with those reported in the Gaia catalogue. For this exercise, we use only CALSPEC stars having STIS observations (i.e. covering the Gaia bandpasses). Further, we remove stars labelled as variable in CALSPEC, and retain only Gaia magnitudes with the designation duplicated_source=0, phot_proc_mode=0 (i.e. “Gold” sources, see Riello et al. 2018). We also remove a handful of stars with flux excess factors (a measure of the inconsistency between $G_{\text{BP}}$, $G$, and $G_{\text{RP}}$ bands typically arising from binarity, crowding and incomplete background modelling) that are significantly higher than those of the rest of the sample (phot_bp_rp_excess_factor<1.3). The resultant comparison is shown in Figure 1. The differences between the computed and observed $G_{\text{BP}}$ and $G_{\text{RP}}$ magnitudes are only a few mmag. However, $G$ magnitudes show a clear magnitude-dependent trend, which in fact is qualitatively in agreement with those shown in the left-hand panels of figures (13) and (24) by Evans et al. (2018). After taking into account the errors in the synthetic magnitudes from CALSPEC flux uncertainties and Gaia measurements, the significance of this slope is close to 5σ. No trend is observed as function of colour. A constant offset between CALSPEC and Gaia synthetic magnitudes would indicate a difference in zero-points or absolute calibration, simply confirming intrinsic limitations on the current absolute flux scale (which linchpin on Vega’s flux at 5555 Å for CALSPEC, and 5500 Å for Gaia). A drift of the CALSPEC absolute flux scale at fainter magnitudes would appear in all filters: the fact no trend is seen for $G_{\text{BP}}$ nor $G_{\text{RP}}$ magnitudes likely indicates that the cause of the problem stems from Gaia $G$ magnitudes instead. The sign of this trend implies that Gaia $G$ magnitudes are brighter than synthetic CALSPEC photometry for $G \leq 14$, although for a few stars this occurs at $G \sim 12$. Understanding the origin of this deviation is outside the scope of this letter. Here we provide a simple fit to place Gaia $G$ magnitudes onto the same CALSPEC scale as for $G_{\text{BP}}$ and $G_{\text{RP}}$ magnitudes:

$$G_{\text{cont}} = 0.0505 + 0.9966G,$$  \(3\)

which applies over the range $6 \leq G \leq 16.5$ mag. While brighter $G$ magnitudes in Gaia are affected by saturation (the trend found by Evans et al. 2018 using Tycho2 and Hipparcos photometry is also seen by us, see Figure 1), it remains to be seen whether the offset that we find extends to magnitudes fainter than 16.5.

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1. http://www.stsci.edu/hst/observatory/crds/calspec.html

2. In all instances, flux uncertainties from CALSPEC and Gaia are small enough that the skewness of mapping fluxes into magnitudes has no impact, but see Paper I, Appendix B for a discussion of this effect.
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3 ON BOLOMETRIC CORRECTIONS AND OTHER UNCERTAINTIES ON STELLAR LUMINOSITIES

We refer to Paper I and II for a description of the MARCS grid, our interpolation routines, and examples of their use for different input reddenings (in all cases we have adopted the Cardelli et al. 1989 parametrization of the extinction law). We also emphasize once more the importance of paying attention to the zero-point of the bolometric magnitude scale, which is arbitrary, but once chosen, must be abided. In our grid, there is no ambiguity in the zero-point of the BCs, which is instead an unnecessary source of biases when matching a synthetic grid to heterogeneous observations (Andrae et al. 2018). To derive BCs from our grid requires the prior knowledge of stellar parameters, which often might not be a trivial task. Our scripts easily allow one to test the effects on BCs of varying the input stellar parameters. Projecting BCs as function of Teff would also be affected by the distribution of stellar parameters underlying the grid. In nearly all circumstances, this distribution would be different from that of the sample used for a given investigation.

In Paper I and II we carried out extensive tests of the MARCS synthetic colours and BCs against observations, concluding that observed broad-band colours are overall well reproduced in the range encompassed by the Gaia bandpasses, with the performance degrading towards the blue and ultraviolet spectral regions. For the sake of this letter, we want to know how well bolometric fluxes can be recovered from Gaia photometry. In fact, Gaia parallaxes deliver exquisite absolute magnitudes for a large fraction of stars (Gaia Collaboration et al. 2018b). However, when comparing them with stellar models, one of the main limiting factors stems from the quality of the BCs. Here we extend the comparison of Table 2 in Paper II (which is limited by the availability of reliable stellar parameters to F and G dwarfs at various metallicities) to include Gaia G*BP, G, and G*RP magnitudes. Our goal is to assess how well our BCs recover the bolometric fluxes measured from the CALSPEC library. This is shown in Figure 2. The first thing to notice is the offset, as well as scatter associated with the BCs in G*BP. While the synthetic photometry presented in Figure 1 only relies on the observed spectrophotometry and how well a bandpass is standardized, the quality of the comparison in Figure 2 also depends on the MARCS models, as well as the input stellar parameters that were adopted when our tables of BCs were interpolated. As already mentioned, the performance of the MARCS models degrades toward the blue, and in this spectral region, the fluxes have a stronger dependence on stellar parameters. The comparison is better in G*RP band (bottom right) as well as in the G band (top panels). In the latter case, applying Eq. 3 to correct the Gaia photometry improves the agreement, but it does not yield to a perfect match (for the same reasons that were just discussed). In all cases, the offset and scatter typically vary between 1 and 2 percent, which we regard as the uncertainty of our BCs (0.01–0.02 mag for the F and G dwarfs tested here).

To summarize, we now estimate the fractional contribution of different uncertainties to stellar luminosities. Assuming systematic errors in magnitudes are under control (or corrected for, as we discussed), the precision of Gaia magnitudes σG is typically at the mmag level (although larger for sources that are very bright, in crowded regions, or very faint) meaning they contribute with a negligible 0.4 ln(10)σG to the luminosity error budget. Other contributions amount to 0.4 ln(10)RBP σE(B-V) for reddening, 0.4 ln(10)σBC for BCs, and 2σω/ω for parallaxes. This implies that the uncertainty in BCs is dominant over the parallax error when σBC ≥ 2.2σω/ω. In other words, when parallaxes are better than 0.5%, BCs are the dominant source of uncertainty if σBC ~ 0.01. This is shown by the purple line in Figure 3 where the interplay among different uncertainties for a target luminosity error is explored.

Figure 2. Percentage difference between bolometric fluxes from CALSPEC photometry, and those recovered from our BCs (bands indicated in the top left corner of each panel). The stars and parameters that were adopted in our interpolation routines are the same as in Table 2 of Paper II. Filled circles are stars satisfying quality requirements listed in Section 2.1. Open circles are stars with duplicated_source=1 (which may indicate observational, cross-matching or processing problems, or stellar multiplicity, and probable astrometric or photometric problems in all cases). Errors bars are obtained assuming a fixed 1 percent uncertainty in CALSPEC fluxes, and MonteCarlo simulations taking into account the quoted uncertainties in both the input stellar parameters and observed photometry for each target. Continuous blue lines indicate median offsets, dotted lines centred at zero are used to guide the eye. BCs from the Gaia-DR2 set are used in all instances, although nearly identical results are obtained using the Gaia-pro and Gaia-rev sets.

Bolometric flux (erg s⁻¹ cm⁻²) implies the flux across the entire spectrum that an observer (us) would measure from a star at distance d. On the other hand, luminosity (erg s⁻¹) refers to the intrinsic energy output of a star, i.e., 4πd² times the bolometric flux.
4 THE COLOURS OF THE SUN AND VEGA

The solar colours provide an important benchmark point in many areas of astronomy and astrophysics. The least model dependent, and arguably the best method to determine them relies on solar twins (Meléndez et al. 2010; Ramírez et al. 2012; Casagrande et al. 2012). Here we use instead the formalism developed for Gaia synthetic magnitudes to compute solar colors from a number of high fidelity, flux calibrated spectra. From the CALSPEC library we use a Kurucz model (sun_mod_001.fits) and a solar reference spectrum (sun_reference_stis_002.fits) which combines absolute flux measurements from space and from the ground with a model spectrum longward of 9600Å (Colina et al. 1996). We also use the Thuillier et al. (2004) spectra for two solar active levels (about half of a solar cycle), where in fact the difference between them is well below 1 mmag across the Gaia filters (hence we report only one set). Similarly, we can also use two spectra of Vega available on the CALSPEC library to estimate its magnitudes and colours (the Kurucz model alpha_lyr_mod_002.fits, and alpha_lyr_stis_008.fits which intermingles a Kurucz model with HST-STIS measurement across part of the G and G ′ bands). We remark that the Gaia system is tied to Vega (assigned to have 0 magnitudes in all bands) using a slightly different Kurucz model, and absolute flux calibration than CALSPEC. Hence, if we generate magnitudes following the Gaia formalism, and believe CALSPEC to better match the actual flux of Vega, it is not surprising that its magnitudes will be slightly different from 0. As it can be seen from Table 1 there is excellent agreement in the magnitudes and colours obtained from different spectral templates, with differences of only a few mmag, comparable to the precision reached by Gaia. At the level of 0.01 mag, it is thus possible to quote robust numbers for the Sun and Vega’s magnitudes, independently of the adopted spectral template, and flavour of zero-points and transmission curves. In the Vega system we have $G_0 = 8.79$, corresponding to an absolute magnitude of $M_G = 4.67$, $(G_{BP} - G)_0 = 0.33$, $(G - G_{RP})_0 = 0.049$ and $(G_{RP} - G)_0 = 0.282$ for the Sun, and $G = 0.03$, $(G_{BP} - G) = 0.005$, $(G - G_{RP}) = 0.01$ and $(G_{RP} - G_{BP}) = 0.015$ for Vega. Finally, in Table 2 we report extinction coefficients for the Gaia filters, both average, and $T_{eff}$-dependent ones. Users interested in extinction coefficients at different values of temperature and/or metallicities can easily derive them from our routines.

5 CONCLUSIONS

Gaia, not least its photometry, will induce a paradigm shift in many areas of astronomy. However, to make full use of these data, colour predictions from stellar fluxes are mandatory, as well as control of systematics. We have expanded our previous investigations using MARCS stellar fluxes to include Gaia $G_{BP}$, $G$, and $G_{RP}$ magnitudes. In doing so, we have explored the effects of implementing the two different sets of bandpasses and zero-points that have been released with Gaia DR2. Differences are typically of few mmag only. Further, we have generated a third set, which takes into account the Gaia Collaboration et al. (2018a) recommendations to provide the best match to observations. All of these sets are available as part of our interpolation package for users to explore. In examining the adopted zero-points, we uncovered a magnitude-dependent offset in Gaia $G$ magnitudes. Albeit small, this trend amounts to 30 mmag over 10 magnitudes in the $G$ band, which is larger than systematic effects at the 10 mmag level quoted by Evans et al. (2018). This offset is relatively small, but it potentially has a number of implications should $G$ magnitudes be used, e.g., to calibrate distance indicators. Despite this offset, we regard Gaia magnitudes as an incredible success, delivering magnitudes for a billion sources with an accuracy within a few percent of CALSPEC.

We also carried out an evaluation of the quality of our BCs, and their impact on the luminosity error budget. $G$ and $G_{BP}$ magnitudes are typically better than $G_{RP}$ in recovering bolometric fluxes, although averaging different bands is probably advisable whenever possible. Also, the systematic trend uncovered in $G$ magnitudes does not impact bolometric fluxes too seriously, since uncertainties in adopted stellar parameters and the performance of the synthetic MARCS fluxes enter the error budget with a similar degree of un-
Based on the differences in the bolometric corrections for $E(B - V) = 0.0$ and 0.10, assuming log $g = 4.1, -2.0 \leq [\text{Fe/H}] \leq +0.25$, with $[\alpha/\text{Fe}] = -0.4, 0.0$ and 0.4 at each $[\text{Fe/H}]$. Note that $T_\text{eff} = 10^4 T_{\text{eff}}$. For a given nominal $E(B - V)$, the excess in any given $\zeta - \eta$ colour is $E(\zeta - \eta) = (R_\zeta - R_\eta)E(B - V)$, and the attenuation for a magnitude $m_\zeta = R_\zeta E(B - V)$.

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