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Transformations from standard photometric systems to the *Gaia* passbands

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Transformations from standard photometric systems to the *Gaia* passbands

A Ritter[1] and C Huang[2]

[1] Laboratory for Space Research, Hong Kong University, Pokfulam Rd, Hong Kong (SAR China), (E-mail: azuri.ritter@gmail.com)
[2] Chongqing Foreign Language School, Hongyupo St., Jiulongpo District, Chongqing Province, China

azuri.ritter@gmail.com; acidhuang@gmail.com

Abstract. Aims. Provide a transformation from the standard photometric filters to *Gaia G,* G_{BP} *and* G_{RP} passbands. Methods. The relations between the standard photometric filters in the Johnson-Cousins *UBV* R_C I_C photometric system, the SDSS *ugriz* system, and the *Gaia* passbands were fitted with up to third order polynomials for dwarfs and giants individually. Results. At least for the *Gaia* G_{BP} passband the Johnson-Cousins filter are better suited for a reliable prediction. No improvement is seen for higher than third order polynomial fits for any of the performed transformations. Conclusions. The provided dependencies amongst colours can be used to transform the apparent magnitudes in the *B*, *V*, R_C, and SDSS *griz* passbands to *Gaia G*, G_{BP}, and G_{BR} photometry, allowing for a comparison of the Gaia survey to models of the Galaxy and to previous large surveys.

1. Introduction

The *Gaia* mission is a space telescope of European Space Agency (ESA), which is designed to chart a three-dimensional map of one billion stars in our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy (http://sci.esa.int/gaia/). This massive stellar census will provide the basic observational data to analyze a wide range of important questions related to the origin, structure, and evolutionary history of our galaxy which has never been done before.

Models of the Galaxy like Galaxia[1] do not predict the *Gaia* passbands, only standard photometric systems like Johnson Cousins *UBV* R_C I_C[2] or Sloan Digital Sky Survey[3] *ugriz* are implemented. To compare the *Gaia* survey to models of the Galaxy as well as previous large photometric surveys of the Galaxy, a transformation from these standard photometric systems to the *G*, G_{BP}, and G_{BR} passbands is needed.

Prior to the start of *Gaia* observations, Jordi et al. [4] derived theoretic transformation relations between the GAIA *G*, G_{BP}, and G_{RP} and the Johnson-Cousins *UBV* R_C I_C system, the SDSS *ugriz* system, and the Hipparcos photometric system. The primes refer to the filter-detector combination envisioned to be used at the *Gaia* mission. For the colour transformations they calculated synthetic spectra from the BaSeL library[5]. These synthetic magnitudes were then used to determine photometric transformations. Since then the 2nd data release has become available, providing the actual measurements, making the theoretical transformations obsolete. Here we provide magnitude transformations from the Johnson-Cousins *UBV* $R_C I_C$ and SDSS *ugriz* passbands to the *Gaia* *G*, G_{BP}, and G_{RP} passbands using actual measurements. In chapter 2 we will provide an overview of the *Gaia* passbandand the standard photometric systems. In chapter 3 we will describe the data set and in chapter 4 derive a transformation from the stellar magnitudes in the Johnson-Cousins and SDSS photometric systems to the *Gaia* passband.

2. Gaia passbands and standard photometric systems

In Figure 1 the normalized passbands of the *Gaia* survey are shown together with the Johnson-Cousins and the SDSS filters. As can be seen in the figure, to derive the apparent magnitude in the blue *Gaia* G_{BP} passbands either the Johnson-Cousins *BV* R_C magnitudes or the SDSS *gr* magnitudes can be used while the Johnson-Cousins $R_C I_C$ or the SDSS *riz* provide the information to derive the magnitude in the red *Gaia* G_{RP} channel. The *Gaia G* band is the combination of the G_{BP} and G_{RP} passbands.

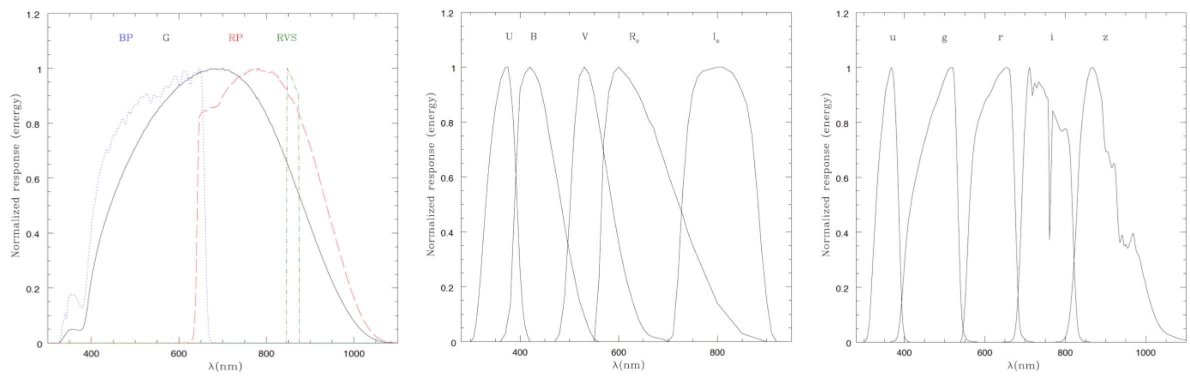


Figure 1. *Gaia*, Johnson-Cousins, and SDSS normalized passbands.

3. The data set

To get the Johnson-Cousins and SDSS magnitudes for stars observed by *Gaia* we cross-matched the *Gaia* DR2 catalogue[6][7] with the SIMBAD astronomical database[8]. This led to ~ 9, 700, 000 stars. For ~ 252, 000 of these previous measurements of the Johnson-Cousins *BV* R_C magnitudes (~ 125, 000 dwarfs,~ 127, 000 giants) exist. The simple cross-match using the CDS X-Match interface at http://cdsxmatch.u-strasbg.fr/ did not give the Cousins I_C band so we manually downloaded ~ 175, 000 from the SIMBAD database. We then separated dwarfs and giants by their surface gravities given in the *Gaia* DR2 catalogue. Again unfortunately, cross-matching the SIMBAD stars with I_C magnitudes to the *Gaia* DR2 only lead to 6 stars for which the *Gaia* surface gravities are given. This means that fitting the *Gaia* G_{RP} and *G* magnitudes from the Johnson-Cousins filter set will have to wait until the *Gaia* DR3.

For the SDSS *ugriz* magnitudes we cross-matched the SDSS DR12 with the *Gaia* DR2 which resulted in ~ 346, 000 stars with *gr* magnitudes (~ 165, 000dwarfs, ~ 181, 000 giants), ~ 38, 000 stars for which the *riz* magnitudes are given (~ 12, 900 giants, ~ 25, 400 giants), and 1,351 stars with *griz* magnitudes (778 dwarfs, 573 giants).

4. The transformation procedure

For the transformation from the given Johnson-Cousins and SDSS magnitudes to the *Gaia* G_{BP} , G_{RP} , and *G* passbands we fitted equations 1 to 4 using standard least squares polynomial regression from first degree to sixth degree. As there was no improvement from the third degree on-wards for any of the relations, only the results for the first three degrees are given here. Note that for the G_{BP} ($BV\,R_C$) no major improvement was achieved after the first degree. During the fitting procedure we kept back 10% of the stars to test the resulting fit.

$$G_{BP}(BVR) = c_1 + \sum_{i=1}^{n} c_{i+1}B^i + \sum_{j=1}^{n} c_{j+1+n}V^j + \sum_{k=0}^{n} c_{k+1+2n}R^k$$

$$G_{BP}(gr) = c_1 + \sum_{i=1}^{n} c_{i+1}g^i + \sum_{j=1}^{n} c_{j+1+n}r^j$$

$$G_{RP}(riz) = c_1 + \sum_{i=1}^{n} c_{i+1}r^i + \sum_{j=1}^{n} c_{j+1+n}i^j + \sum_{k=1}^{n} c_{k+1+2n}z^k$$

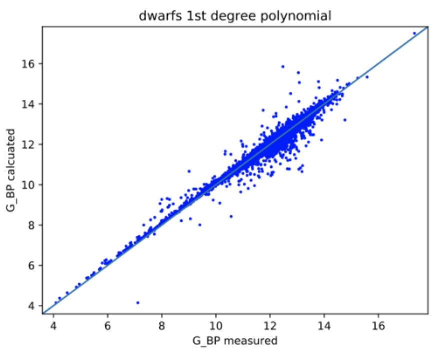
$$G_{RP}(griz) = c_1 + \sum_{i=1}^{n} c_{i+1}g^i + \sum_{j=1}^{n} c_{j+1+n}r^j + \sum_{k=1}^{n} c_{k+1+2n}i^k + \sum_{l=1}^{n} c_{l+1+3n}z^l$$

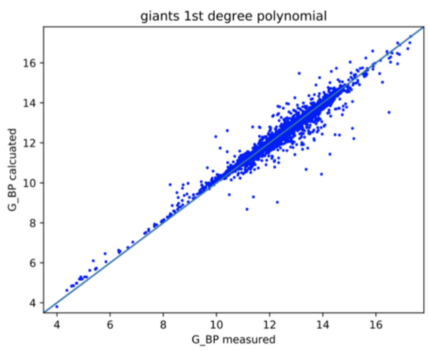
5. Results

The fitted coefficients as well as the resulting mean offset and standard deviation are given in Tables 1-6. The transformation from the Johnson-Cousins $B_V\,R_C$ magnitudes to the *Gaia* G_{BP} passband (Figure 2) appears to be almost perfectly linear with a mean error in the test stars of $1.9*10^{-4}$ and a standard deviation of 0.19 magnitudes. On the contrary, the polynomial transformations from the SDSS *ugriz* filters are non-linear with quite large mean differences and standard deviations as well as strong systematics, some of which are increasing with the degree of the fitting polynomial like the cut off in the calculated maximum *Gaia* passbands (figure 3 - 5). In order to identify the reasons for the discrepancies between the measured *Gaia* G_{BP} , G_{RP} , and G passbands and the ones calculated from the SDSS *ugriz* filters more research is needed. Possible reasons include inter stellar extinction, different stellar populations, or that the *ugriz* filters are simply not exactly suitable for a prediction of the *Gaia* passbands.

Acknowledgement

This work has made use of data from the European Space Agency (ESA) mission*Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.





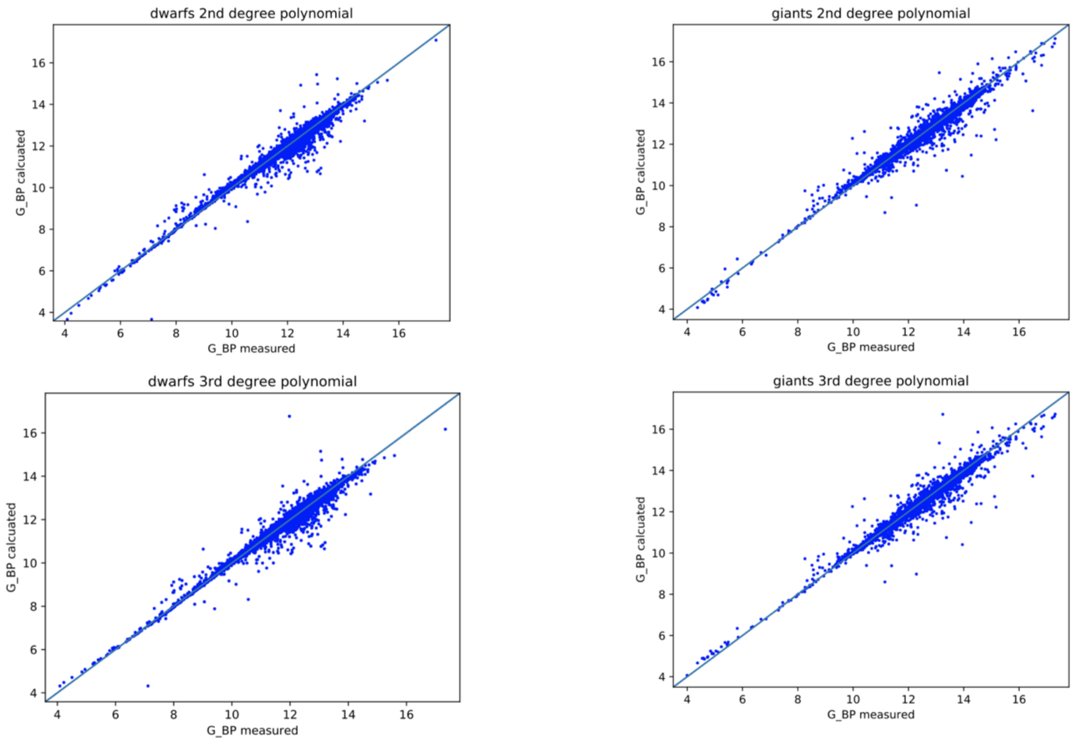
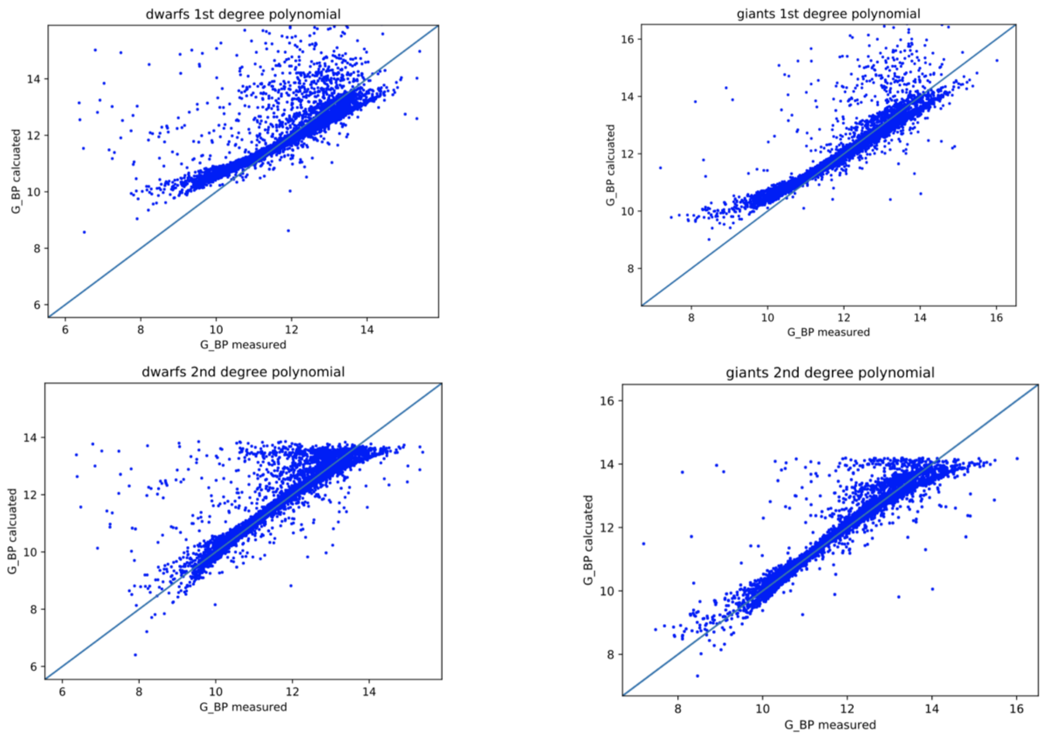


Figure 2. G_{BP} calculated from Johnson Cousins *BV* R_C versus measured values in the *Gaia* DR2. top: first degree polynomial fit, center: second degree polynomial, bottom:third degree polynomial.



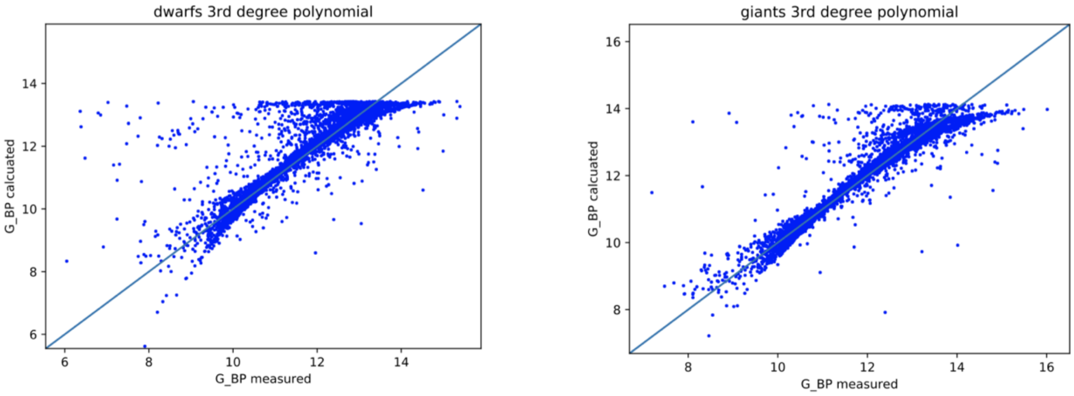


Figure 3. G_{BP} calculated from SDSS *gr* versus measured values in the *Gaia* DR2. top: first degree polynomial fit, center: second degree polynomial, bottom: third degree polynomial

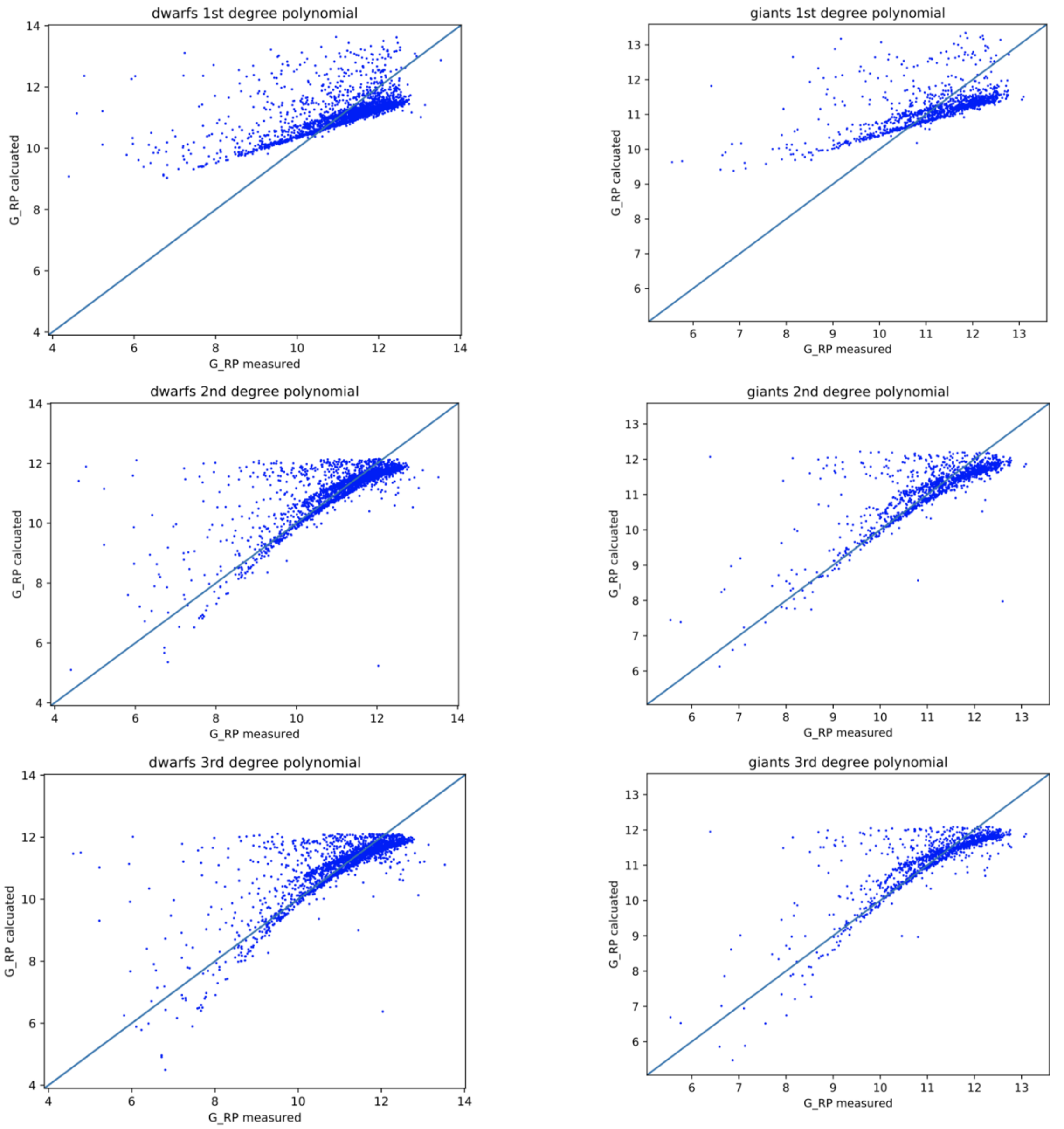


Figure 4. G_{RP} calculated from SDSS *riz* versus measured values in the *Gaia* DR2. top: first

degree polynomial fit, center: second degree polynomial, bottom: third degree polynomial.

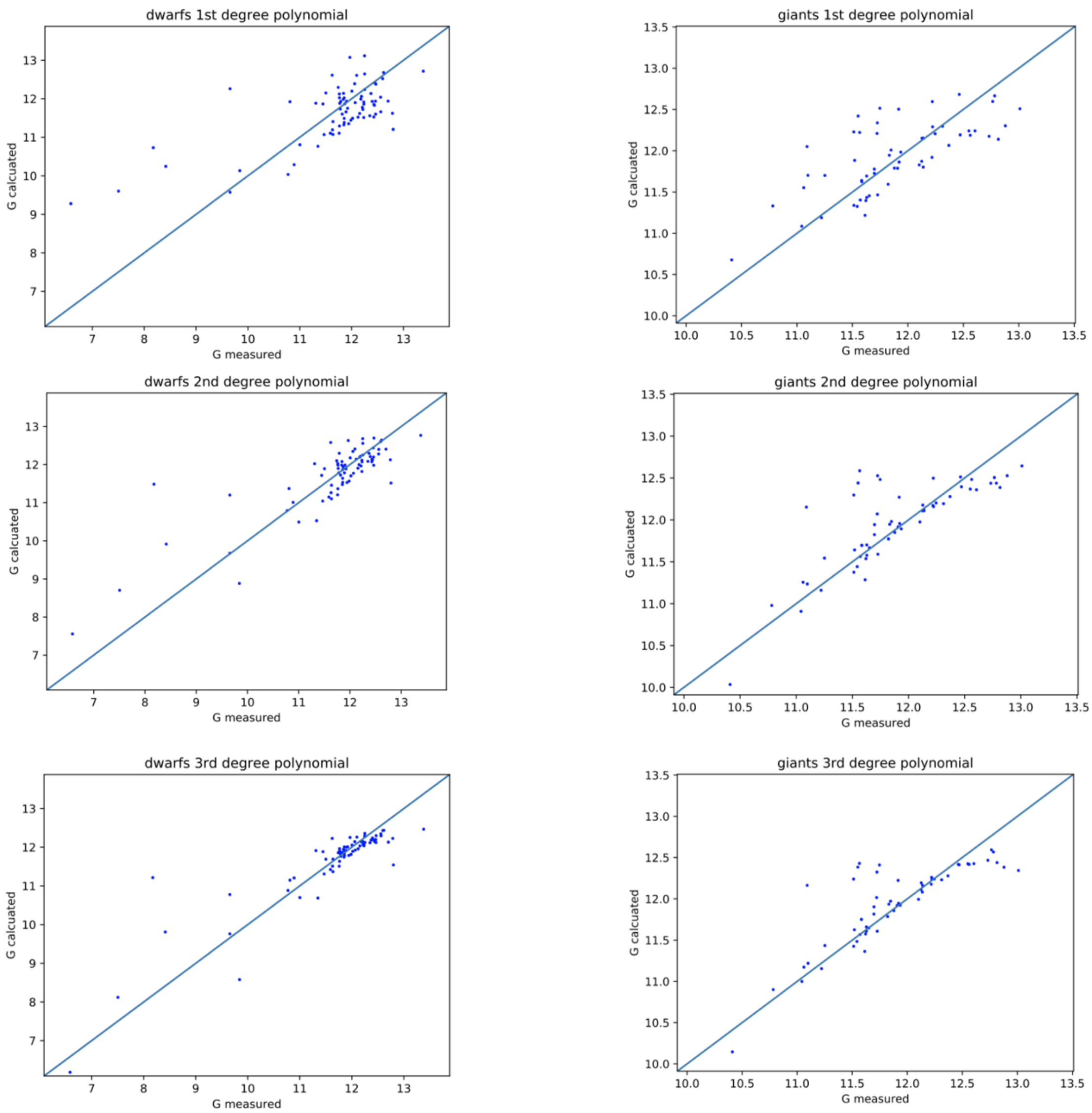


Figure 5. *G* calculated from SDSS *griz* versus measured values in the *Gaia* DR2. top: first degree polynomial fit, center: second degree polynomial, bottom: third degree polynomial.

Table 1. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for dwarfs.

	$G_{BP}(BV\ R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	0.310369	3.625495	5.951392	4.146459
c_2	0.218680	0.237635	0.149555	0.254721
c_3	0.631294	0.465199	0.092355	-0.103545
c_4	0.132206		0.172743	-0.054533
c_5				0.484768
μ	-0.000189	-0.007448	-0.004040	0.032761
σ	0.190972	0.584696	0.945914	0.805667

Table 2. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

	$G_{BP}(BV\,R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	0.666924	2.249222	6.176202	4.198003
c_2	0.185286	0.235376	0.126755	0.119677
c_3	0.561372	0.602905	0.084687	0.106207
c_4	0.210602		0.186384	0.160173
c_5				0.231903
μ	-0.003102	0.000595	0.010074	-0.033474
σ	0.191159	0.386485	0.875289	0.382508

Table 3. Fitted coefficients, mean and standard deviation for the second degree polynomial fits for dwarfs.

	$G_{BP}(BV\,R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	-0.91378	-15.69654	-14.78702	-22.16134
c_2	0.721155	1.239950	1.142767	1.258016
c_3	-0.018940	-0.034084	-0.038214	-0.039272
c_4	0.132443	2.592306	0.923657	0.919809
c_5	0.019209	-0.091875	-0.031312	-0.033691
c_6	0.322033		1.545787	0.589868
c_7	-0.007980		-0.051574	-0.018771
c_8				1.797389
c_9				-0.056034
μ	-0.000447	-0.008341	0.000665	-0.017272
σ	0.185581	0.398462	0.763849	0.612686

Table 4. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

	$G_{BP}(BV\,R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	-0.217718	-15.07683	-13.91357	-31.78120
c_2	-0.013548	1.478522	1.309409	2.666026
c_3	0.007131	-0.043223	-0.043097	-0.091417
c_4	0.717688	2.173337	0.548252	-0.430592
c_5	-0.006528	-0.071029	-0.016964	0.019644
c_6	0.441414		1.606988	2.483974
c_7	-0.009929		-0.054868	-0.091234
c_8				1.561002
c_9				-0.058925
μ	-0.002944	2.88056e-05	0.006737	-0.061931
σ	0.188810	0.242389	0.653224	0.332321

Table 5. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

	$G_{BP}(BV R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	2.226383	-29.06283	-25.56785	-76.85359
c_2	-0.353839	3.621387	0.858047	3.414742
c_3	0.058666	-0.172525	-0.024775	-0.187714
c_4	-0.001828	0.002437	-0.000123	0.003319
c_5	0.867954	3.102114	1.372153	0.919800
c_6	-0.016598	-0.159801	-0.067678	-0.040800
c_7	0.000212	0.002409	0.000980	0.000339
c_8	-0.238736		3.790849	5.169708
c_9	0.036222		-0.203173	-0.320387
c_{10}	-0.001110		0.003234	0.006244
c_{11}				7.066260
c_{12}				-0.445247
c_{13}				0.009068
μ	-2.404e-05	-0.008322	-0.000893	0.016682
σ	0.179626	0.387548	0.695427	0.517406

Table 6. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

	$G_{BP}(BV R_C)$	$G_{BP}(gr)$	$G_{RP}(riz)$	$G_{RP}(griz)$
c_1	2.381257	-21.95001	-31.1624	-25.12979
c_2	-0.526924	3.14909	1.675185	-7.370948
c_3	0.039339	-0.145094	-0.087660	0.605977
c_4	-0.000644	0.001962	0.001488	-0.016096
c_5	1.426873	1.942623	2.154728	6.564208
c_6	-0.051102	-0.069980	-0.113986	-0.420398
c_7	0.000822	0.000399	0.001822	0.008748
c_8	-0.527098		3.515393	2.799617
c_9	0.077851		-0.195116	-0.151650
c_{10}	-0.002587		0.003278	0.002441
c_{11}				3.523690
c_{12}				-0.250215
c_{13}				0.005969
μ	-0.003211	-0.000168	0.001353	-0.051005
σ	0.183222	0.238304	0.602439	0.306215

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