Transformations from standard photometric systems to the Gaia passbands

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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 $UBVRCIC$ 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 $B$, $V$, $RC$, and SDSS $griz$ passbands to Gaia $G$, $G_{BP}$, and $G_{RP}$ 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 Galaxia¹ do not predict the Gaia passbands, only standard photometric systems like Johnson Cousins $UBVRCIC$² or Sloan Digital Sky Survey³ $ugriz$ 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 $G_{RP}$ 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 $UBVRCIC$ 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 library⁵. 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 $UBV_{RC}$ 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 passband and 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 $BV_{RC}$ magnitudes or the SDSS $gr$ magnitudes can be used while the Johnson-Cousins $RC_{IC}$ 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.](image)

3. The data set

To get the Johnson-Cousins and SDSS magnitudes for stars observed by Gaia we cross-matched the Gaia DR2 catalogue with the SIMBAD astronomical database. This led to ~ 9,700,000 stars. For ~ 252,000 of these previous measurements of the Johnson-Cousins $BV_{RC}$ magnitudes (~ 125,000 dwarfs, ~ 127,000 giants) exist. The simple cross-match using the CDS X-Match interface at [http://cdsxmatch.u-strasbg.fr/](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 $G_{BP}$ 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 (~ 165,000 dwarfs, ~ 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 onwards for any of
the relations, only the results for the first three degrees are given here. Note that for the $G_{\text{BP}}$ ($B V R$) 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.

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

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

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

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

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 $B V R$ magnitudes to the Gaia $G_{\text{BP}}$ passband (Figure 2) appears to be almost perfectly linear with a mean error in the test stars of $1.9 \times 10^{-4}$ 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 $G_{\text{BP}}$, $G_{\text{RP}}$, 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.

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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](image)

**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.

|       | $G_{BP}(BV_{RC})$ | $G_{BP}(gr)$ | $G_{BP}(riz)$ | $G_{BP}(griz)$ |
|-------|-------------------|--------------|---------------|----------------|
| $c_1$ | 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     | 0.032761      | 0.054533       |
| $c_5$ |                   |              | 0.484768      |                |
| $\mu$ | -0.000189         | -0.007448    | -0.004040     | 0.032761       |
| $\sigma$ | 0.190972       | 0.584696     | 0.945914      | 0.805667       |
Table 2. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

|      | $G_{BP}(BV_{RC})$ | $G_{BP}(gr)$ | $G_{RP}(riz)$ | $G_{RP}(griz)$ |
|------|-------------------|--------------|---------------|----------------|
| $c_1$ | 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       |
| $\mu$ | -0.003102         | 0.000595     | 0.010074      | -0.033474      |
| $\sigma$ | 0.191159         | 0.386485     | 0.875289      | 0.382508       |

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

|      | $G_{BP}(BV_{RC})$ | $G_{BP}(gr)$ | $G_{RP}(riz)$ | $G_{RP}(griz)$ |
|------|-------------------|--------------|---------------|----------------|
| $c_1$ | -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     |                |
| $\mu$ | -0.000447         | -0.008341    | 0.000665      | -0.017272      |
| $\sigma$ | 0.185581         | 0.398462     | 0.763849      | 0.612686       |

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

|      | $G_{BP}(BV_{RC})$ | $G_{BP}(gr)$ | $G_{RP}(riz)$ | $G_{RP}(griz)$ |
|------|-------------------|--------------|---------------|----------------|
| $c_1$ | -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     |                |
| $\mu$ | -0.002944         | 2.88056e-05  | 0.006737      | -0.061931      |
| $\sigma$ | 0.188810         | 0.242389     | 0.653224      | 0.332321       |
Table 5. Fitted coefficients, mean and standard deviation for the first degree polynomial fits for giants.

|    | \(G_{BP}(BV\,RC)\) | \(G_{BP}(gr)\) | \(G_{BP}(riz)\) | \(G_{BP}(griz)\) |
|----|---------------------|----------------|-----------------|-----------------|
| \(c_1\) | 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        |                 |
| \(\mu\) | -2.404e-05         | -0.008322      | -0.000893       | 0.016682        |
| \(\sigma\) | 0.179626           | 0.387548       | 0.695427        | 0.517406        |

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

|    | \(G_{BP}(BV\,RC)\) | \(G_{BP}(gr)\) | \(G_{BP}(riz)\) | \(G_{BP}(griz)\) |
|----|---------------------|----------------|-----------------|-----------------|
| \(c_1\) | 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        |                 |
| \(\mu\) | -0.003211           | -0.000168      | 0.001353        | -0.051005       |
| \(\sigma\) | 0.183222           | 0.238304       | 0.602439        | 0.306215        |
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