GAIA Photometric Performances

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Abstract. GAIA present day (end-2002) photometric performances, estimated basing on the stellar populations crucial for understanding the formation and evolution of the Galaxy, are discussed. Performance of the GAIA photometric systems (PSs) is evaluated taking into account their ability to simultaneously determine the main stellar parameters: $T_{\text{eff}}$, $\log g$, $[\text{M/H}]$, and $E_{B-V}$, for a large variety of stars down to $V \sim 20$. A sample of the stars (Photometric System Test Targets, PSTTs) applicable for evaluation of the GAIA photometric systems is presented. Definitions of the 1X PS and its accuracies of stellar parameterization are given. We conclude that there is still no photometric system, which would allow to achieve the scientific objectives of the GAIA mission at the limiting magnitude $V = 20$, proposed to date.

1. Introduction

Though the primary goal of the GAIA mission is a study of the Galactic dynamics, photometric as well as spectroscopic observations are also of great importance in order to achieve the main GAIA objectives (ESA 2000). Therefore, an optimal multicolour photometric system, adequate to the main mission goals, has to be designed and analysed in detail. One of the most important steps towards such a PS is an elaboration of a method for unbiased evaluation of the PSs proposed for GAIA in terms of the accuracy of stellar parameters derived (Vansevičius, Bridžius, & Drazdys 2002). A tight time schedule of the pre-launch preparation constrains possibilities of thorough testing of the new PS on real sky objects. Therefore, optimization and further choice of the most suitable PS for the GAIA mission must be entirely based on the synthetic and observed spectral energy distributions (SEDs) and the representative set of a large variety of stellar populations and interstellar medium inside the Galaxy.

We would like to note two key points which have been taken into account for evaluating the GAIA PSs in the present study. The same GAIA observation (Deveikis, Bridžius, & Vansevičius 2002) and parameterization (Bridžius & Vansevičius 2002) methods have been applied to all PSs, and the performance of
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the PSs has been tested on the PSTT stars, which are of the highest importance to the GAIA mission (ESA 2000).

2. Requirements for the GAIA Photometric System

The primary objective of the GAIA mission is to obtain data which allows us to study the composition, formation and evolution of the Galaxy. This priority also constrains the requirements for the GAIA PS. Therefore, metallicity and age variations (RGB, AGB and HB), star formation history (SFH) over the last 14 Gyr (A-K MS stars), and dust distribution within the Galaxy are the most important issues to be assessed by the GAIA PS.

The variety of the object types and astrophysical circumstances presuppose specific requirements for the GAIA PS performance. It is indisputable that the four main parameters ($T_{\text{eff}}$, $\log g$, $[M/H]$, and $E_{B-V}$) ought to be derived as precisely as possible at the limiting magnitude of the survey, $V = 20$. However, it is very important to decide which parameters should be determined additionally. Therefore, below we list the most relevant items whose various degree of treatment could significantly influence the final design of the GAIA PS:

- variation of $[\alpha/Fe]$ - should it be determined by PS?
- extinction of the F-K type stars - should it be determined for each individual star by PS or assigned from the 3-D extinction maps?
- binaries - should PS be adapted for their recognition and parameter estimation?
- variable extinction law, $R_{BV}$ - should it be determined by PS?
- chemical peculiarities - should the strong peculiar features (e.g. C, N) be avoided or measured by PS?
- WD, BD, WR, δCep, T Tau, Mira, C, etc. type stars - which parameters should be derived by PS?

Although it is very important to take all mentioned points into account, present day investigations and discussions are devoted mostly to the first two items. Determination of the interstellar extinction of the F-K type stars is fully accounted (Sūdžius et al. 2002) and can be discussed quantitatively. However, the $[\alpha/Fe]$ problem is still pending due to lack of a proper grid of SEDs. Therefore, only these two items are taken into account for selection of the PSTTs.

3. GAIA Photometric System Test Targets (PSTTs)

According to ESA (2000), the stars to be observed with GAIA down to $G \sim 20$ can be roughly represented by the following proportions of stellar populations (Ms - stands for millions of stars):

- the total number of stars of all types $\gtrsim 1000$ Ms;
- disk dwarfs $\sim 780$ Ms; disk giants $\sim 90$ Ms;
Figure 1. GAIA Photometric System Test Targets (PSTTs).

- thick disk (all types) $\sim 100$ Ms; halo (all types) $\sim 70$ Ms;
and spectral types:

- O-B $\sim 2$ Ms; A $\sim 50$ Ms; F $\sim 230$ Ms;
- G $\sim 400$ Ms; K $\sim 300$ Ms; M $\sim 55$ Ms.

In order to evaluate any PS proposed for GAIA we need to select some set of standard objects with which to test a PS. PSTTs ought to cover the most important stellar population types mentioned above and the most characteristic variety of astrophysical circumstances expected to be encountered in the Galaxy. A set of stellar types which would make up a minimum number of PSTTs is presented in Table 1 and in Figure 1. We need to keep this list as short as possible in order to quickly test any new improvements of the GAIA PSs. However, it should also be comprehensive in the sense of the main GAIA goals. The same statements are also valid for other parameters listed below. The proper choice of the PSTTs is a very important issue for GAIA PS development and optimization, therefore, the list is open for discussions and suggestions.

The list of PSTTs is complemented by other astrophysical parameters, representing circumstances which could be encountered in the Galaxy (Table 2), as completely as possible. Two variants of a complete set of models based on distance, D, of the PSTTs or their apparent magnitude, $V_J$, are foreseen. In
Table 1. GAIA Photometric System Test Targets (PSTTs).

| Code | Sp. Type | T_{\text{eff}} | \log T_{\text{eff}} | \log g | M_{V} |
|------|---------|---------------|------------------|-------|-------|
| 1    | B V     | 14500         | 4.16             | 4.1   | -0.9  |
| 2    | A V     | 8500          | 3.93             | 4.2   | 1.6   |
| 3    | F V     | 6450          | 3.81             | 4.3   | 3.7   |
| 4    | G V     | 5600          | 3.75             | 4.4   | 5.1   |
| 5    | K V     | 4700          | 3.67             | 4.5   | 6.7   |
| 6    | M V     | 3550          | 3.55             | 4.7   | 10.3  |
| 7    | F IV    | 6450          | 3.81             | 3.8   | 2.6   |
| 8    | G IV    | 5600          | 3.75             | 3.6   | 3.1   |
| 9    | G III   | 5150          | 3.71             | 3.0   | 0.9   |
| 10   | K III   | 4150          | 3.62             | 2.5   | 0.3   |
| 11   | M III   | 3550          | 3.55             | 1.2   | -0.5  |
| 12   | BHB     | 8500          | 3.93             | 3.0   | 0.5   |
| 13   | RHB     | 5150          | 3.71             | 2.0   | 0.5   |
| 14   | A I     | 8500          | 3.93             | 2.0   | -5.0  |
| 15   | G I     | 4700          | 3.67             | 1.0   | -4.5  |

order to make a grid of PSTTs convenient for computer modelling and analysis, we suggest to use a complete set of various combinations even if one supposes that any particular combination of the parameters is unrealistic and cannot be found in the Galaxy. Therefore, the complete set of models should contain 5625 different combinations of the parameters in total. Such a task can be easily solved even on a PC type computer.

Table 2. Parameters for the PSTTs. $V_{\text{J}} - UBV$ Johnson system.

| No. | Parameter       | 1   | 2   | 4   | 8   | 20  |
|-----|-----------------|-----|-----|-----|-----|-----|
| 1   | D, kpc          | 1   | 2   | 4   | 8   | 20  |
| 2   | $V_{\text{J}}$  | 15  | 17  | 18  | 19  | 20  |
| 3   | $E_{B-V}$       | 0.05| 0.5 | 1.0 | 1.5 | 3.0 |
| 4   | [M/H]           | +0.5| 0.0 | -0.5| -1.5| -2.5|
| 5   | [$\alpha$/Fe]   | 0.0 | 0.3 | 0.6 | –   | –   |

4. The 1X GAIA Photometric System

Few different photometric systems have been proposed for the GAIA mission to date: 1F (ESA 2000) and its modification 2F, 2A (Munari 1999), 2G and its modification 3G (Høg, Stražys, & Vansevičius 2000). However, the analysis of their performance has demonstrated that none of them satisfy the requirements for the GAIA PS (Vansevičius et al. 2002). Therefore, taking all valuable findings in those PSs into account, a new photometric system, 1X, is proposed.
Evolution of the GAIA PSs and the limiting magnitudes at which they satisfy
GAIA goals are shown in Table 3.

Table 3. Evolution of the GAIA PSs. $V_J$ indicates the limiting mag-
nitude at which PS performance is satisfactory for the GAIA goals.

| Proposed, year | Photometric System | Limit, $V_J$ |
|----------------|--------------------|-------------|
| 1999           | 1F                 | 2G          |
| 2000           |                     | 3G          |
| 2001           | 2F                 |             |
| 2002           | 1X                 | 19          |
| 2003           |                     | 20          |

The filter transmission curves of the 1X medium band (MB) PS de-
dsigned for the Spectro telescope are shown in Figure 2. The central wavelength and
width of the bands as well as a number of slots, allocated for each filter in the
focal plane, are given in Table 4.

Table 4. Definition of the 1X PS. CWL - central wavelength; FWHM
- full width of the filter transmission band at half maximum; NF -
number of slots allocated to the filter in the focal plane.

| Filter | x33 | x38 | x41 | x46 | x51 | x55 | x65 | x78 | x82 | x86 | x99 |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| CWL    | 323 | 382 | 410 | 465 | 510 | 555 | 655 | 785 | 825 | 860 | 992 |
| FWHM   | 63  | 29  | 19  | 29  | 19  | 49  | 29  | 29  | 29  | 29  | 56  |
| NF     | 2   | 2   | 1   | 2   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |

5. Performance of the 1X Photometric System

The performance of the 1X PS is evaluated in terms of its ability to derive basic
stellar parameters: $T_{\text{eff}}$, $\log g$, [M/H], and $E_{B-V}$, for the PSTTs. The procedure
for simulation of the photometric GAIA observations developed by Deveikis et
al. (2002) was used. The simultaneous 4-D stellar parameterization method
(Bridžius & Vansevičius 2002) was applied.

Some specific assumptions on the 1X PS application to the GAIA case
introduced in the modelling procedure should be noted:

- the design of GAIA-1 is assumed as it is given in ESA (2000);
- only the medium band PS is tested assuming that there is no supplem-
entary information obtained from the GAIA broad band (BB) PS (negligible
influence of the BB PS to the performance of MB PS was demonstrated
by Vansevičius et al. 2002);
- the total number of slots for MBP filters is assumed to be equal to 15 (as it
is foreseen in the Radial Velocity Spectrometer (RVS) design for GAIA-2);
Figure 2. The 1X GAIA PS. SEDs of the main sequence stars of $T_{\text{eff}}$: a) 9000 K, b) 5500 K, c) 4500 K, d) 3500 K, are plotted. The numbers of slots allocated to each filter in the focal plane are shown in panel a.

- the maximum of filter transmission curves is set conservatively to 85%;
- modelling is performed by employing the SEDs from BaSeL 2.2 (Lejeune, Cuisinier, & Buser 1998) with solar abundance of $\alpha$-elements, $[\alpha/\text{Fe}]=0.0$;
- the standard ($R_{BV} = 3.1$; Cardelli, Clayton, & Mathis 1989) and invariable extinction law is assumed;
- the aperture photometry procedure is applied for the modelling of star measurement.

The results of the 1X PS performance test are presented in Table 5. The typical value of colour excess, $E_{B-V}$, was assumed for each particular PSTT star. All apparent magnitudes were set to $V = 18$, therefore, each PSTT was placed at some distance, $D$. In order to derive the accuracy of the 1X PS more reliably, 100 independent simulations of each PSTT were performed, and deviations of
the stellar parameters from the true value were determined. The r.m.s. estimate was employed, and the $\sigma$’s of the stellar parameters are tabulated.

Table 5. Performance of the 1X GAIA PS evaluated on PSTTs of solar abundance, $[\text{M/H}]=0.0$, at $V = 18$. SpT – spectral type.

| Code | SpT | $M_V$ | $E_{B-V}$ | D,kpc | $\sigma T_{\text{eff}},\%$ | $\sigma \log g$ | $\sigma [\text{M/H}]$ | $\sigma A_V$ |
|------|-----|-------|-----------|-------|------------------|----------------|------------------|--------|
| 1    | B V | -0.9  | 3         | 0.8   | 4.3              | 0.10           | 1.20             | 0.02   |
| 2    | A V | 1.6   | 1         | 4.6   | 4.0              | 0.15           | 0.30             | 0.09   |
| 3    | F V | 3.7   | 1         | 1.7   | 2.3              | 0.35           | 0.05             | 0.09   |
| 4    | G V | 5.1   | 0.5       | 1.9   | 2.8              | 0.30           | 0.20             | 0.10   |
| 5    | K V | 6.7   | 0.5       | 0.9   | 1.5              | 0.30           | 0.05             | 0.09   |
| 6    | M V | 10.3  | 0.05      | 0.3   | 0.5              | 0.10           | 0.05             | 0.05   |
| 7    | F IV| 2.6   | 1         | 2.9   | 2.8              | 0.25           | 0.05             | 0.10   |
| 8    | G IV| 3.1   | 1         | 2.3   | 3.3              | 0.50           | 0.25             | 0.11   |
| 9    | G III| 0.9  | 1         | 0.6   | 1.0              | 0.45           | 0.05             | 0.03   |
| 10   | K III| 0.3  | 1         | 1.8   | 0.5              | 0.05           | 0.05             | 0.04   |
| 11   | M III| -0.5 | 1         | 0.7   | 0.5              | 0.15           | 0.10             | 0.09   |
| 12   | BHB | 0.5   | 1         | 7.6   | 2.0              | 0.10           | 0.60             | 0.04   |
| 13   | RHB | 0.5   | 1         | 7.6   | 2.0              | 0.55           | 0.15             | 0.08   |
| 14   | A I | -5.0  | 3         | 5.5   | 0.8              | 0.05           | 0.10             | 0.01   |
| 15   | G I | -4.5  | 3         | 4.4   | 1.0              | 0.15           | 0.05             | 0.06   |

We find that performance of the 1X PS at $V = 18$ is excellent and completely satisfies the requirements raised for the GAIA PS by the main GAIA objectives. The performance of the 1X PS is significantly better, especially if cases of higher extinction are considered, comparing to the previous PSs, 2F & 3G (Figures 3 – 5; $V = 18$; the r.m.s. estimates of the parameters were derived basing on 100 simulations of each PSTT; for more details see Vansevičius et al. 2002). The 1X PS also performs satisfactory at $V = 19$, however, there is an obvious necessity to make it more accurate at $V = 20$.

6. Conclusions

We have suggested a set of the GAIA Photometry System Test Targets (PSTTs) selected in order to facilitate easy and comprehensive test of the proposed GAIA PSs. We have introduced a new 1X PS which demonstrates superior performance compared to the PSs proposed for GAIA earlier. The performance of the 1X PS was evaluated taking into account its capability to simultaneously determine the main stellar parameters: $T_{\text{eff}}, \log g, [\text{M/H}],$ and $E_{B-V}$, for the PSTT stars, and assuming that no supplementary information is available, except the data obtained by the GAIA medium band PS.

GAIA is assumed to measure stars in the Galaxy down to $V \sim 20$, however, even the best photometric system (1X) among the PSs, proposed for GAIA to date (end-2002), performs satisfactory only down to $V \sim 19$. Therefore, we conclude that there is still no optimal PS, in terms of the main GAIA mission goals (ESA 2000), proposed to date. However, excellent accuracy of the stellar
parameters determined at $V = 18$ (1X PS) implies fulfilment of the requirements for GAIA PS at $V = 20$ after appropriate fine tuning of each band.

Some gain in performance could be achieved by applying different parameterization schemes for the faintest stars ($V > 18$). Parameterization of these stars should be performed by employing all complementary information obtained by GAIA (parallaxes, spectra, 3-D extinction maps constructed basing on $E_{B-V}$ derived for the brighter stars, $V < 18$, etc.). However, such an automatic parameterization procedure is not yet developed.

In order to optimize the GAIA PS, the following supplemental information is urgently needed:

- a homogeneous and complete database of theoretical stellar spectra, especially SEDs of various [$\alpha$/Fe];

Figure 3. Comparison of the performance of the 1X, 2F, & 3G GAIA PSs, PSTT #2, see Table 1.
realistic estimates of the limiting magnitudes and accuracies of the stellar parameters derived from the RVS data;

determination of the limiting distance, resolution and achievable accuracy of the 3-D extinction maps of the Galaxy;

realistic models of the photometry procedure, taking into account real sky complexity and accuracy of the post-mission calibrations.

Acknowledgments. This work was supported by a Grant of the Lithuanian State Science and Studies Foundation. We are indebted to Valdas Vansevičius for his help on preparation of the article.
Figure 5. Comparison of the performance of the 1X, 2F, & 3G GAIA PSs, PSTT #7, see Table 1.

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