Photometric properties of theoretical spectral libraries for GAIA photometry

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Abstract. Photometric properties of various spectral libraries of synthetic stellar spectra derived from the ATLAS 9 (Castelli et al. 1997), the PHOENIX NextGen (Hauschildt et al. 1998, 1999), the NMARCS (Bessell et al. 1998), and the BaSeL (Lejeune et al. 1998, Westera et al. 2002) models are discussed in view of their application to the definition of the GAIA photometric system. Comparisons with empirical UBVRI calibrations show significant discrepancies at low temperatures between the different models, and with respect to the BaSeL 3.1 and the Alonso et al. (1998, 1999) empirical calibrations.

1. Introduction

The GAIA Galactic survey will observe more than 1 billion of stars in our Galaxy, and will obtain photometry in 11 medium-band and 5 large-band filters with the challenging goal to determine the fundamental stellar parameters ($T_{\text{eff}}$, log $g$, $[\text{Fe/H}]$) across a very wide range of stellar types. In order to test the capabilities of the photometric system and the performances of the classification algorithms, various stellar libraries of synthetic and/or empirical spectra are required. In this study, I compare the photometric properties of the most widely used grids of synthetic spectra (ATLAS, NMARCS, PHOENIX, BaSeL) for cool stars in view of their application to GAIA photometry.

2. Grids of synthetic stellar spectra

The coverage in stellar parameters for each of the grids of models used in this comparative study is given in Table 1. The BaSeL 2.2 hybrid spectral library was constructed from empirical ($[\text{Fe/H}] = 0$) and semi-empirical ($[\text{Fe/H}] \neq 0$) color-temperature relations (see Lejeune et al. 1997, 1998, for details), while the new BaSeL 3.1 models are based on purely empirical calibrations, defined for the metallicity range $-2.0 \leq [\text{Fe/H}] \leq 0.0$ from a large collection of globular cluster UBVRIJHKL photometric data (see Westera et al. 2002 for details). Hence, the BaSeL 3.1 calibrations provide the only existing set of empirical metallicity-dependent $T_{\text{eff}}$-UBVRIJHKL transformations for $-2.0 \leq [\text{Fe/H}] \leq 0.0$ over a large temperature range, from 2000 K to 50000 K, and are used as reference in this study. Synthetic spectra from the ATLAS 9 atmosphere models have been computed by Castelli et al. (1997) with no overshooting parameter.
Table 1. Parameter coverage of the different grids of models

| Models          | Note          | $T_{\text{eff}}$      | $\log g$ | $[\text{Fe/H}]$ | $\lambda$ (nm) |
|-----------------|---------------|-----------------------|----------|-----------------|-----------------|
| BaSeL 2.2\(^{(1)}\) | hybrid lib.   | 2000 - 50000 K        | -1.0 - 5.5 | -5.0 - 1.0     | 9.1 - 1.6 $10^5$ |
| BaSeL 3.1\(^{(2)}\) | hybrid lib.   | 2000 - 50000 K        | -1.0 - 5.5 | -2.0 - 0.5      | 9.1 - 1.6 $10^5$ |
| ATLAS 9\(^{(3)}\)   | no overs.     | 3500 - 50000 K        | 0.0 - 5.0 | -2.5 - 0.5      | 9.1 - 1.6 $10^5$ |
| PHOENIX giants\(^{(4)}\) | 2000 - 7000 K | -0.7 - 0.0            | -0.7 - 0.0 |                 | 10 - 10$^6$     |
| NextGen dwarfs\(^{(5)}\) | 1000 - 7000 K | 3.5 - 6.0             | -4.0 - 0.0 |                 | 10 - 10$^6$     |
| NMARCS\(^{(6)}\) giants | 3600 - 4750 K | -0.5 - 3.5            | -0.6 - 0.6 | BVRIJHK       |
|                | dwarfs        | 2600 - 4000 K         | 4.5 - 5.0 | -2.0 - 0.3      | BVRIJHK        |

\(^{(1)}\) Lejeune et al. 1997, 1998; \(^{(2)}\) Westera et al. 2002; \(^{(3)}\) Castelli et al. 1997; \(^{(4)}\) Hauschildt et al. 1999a; \(^{(5)}\) Hauschildt et al. 1999b; \(^{(6)}\) Bessell et al. 1998.

3. Comparisons in the two-color diagrams

In Fig. 1, model colors in the range $2500K \leq T_{\text{eff}} \leq 5500K$, computed from the different grids of synthetic spectra given in Table 1, are compared in the (B-V)/(V-I) color-color diagram for the same value of the surface gravity ($\log g = 1$) with $[\text{Fe/H}] = -0.6$, $-0.3$ and $0.0$. From the figure, it is clear that large differences exist between the different grids, specially in the low temperature regime ($T_{\text{eff}} < 4000K$). Above 4000 K, the NMARCS models provide the best overall agreement with the BaSeL 3.1 empirical calibrations, both in B-V and V-I, in particular for the solar metallicity. In contrast, the PHOENIX models appear too blue in B-V, while they are in good agreement with the BaSeL 3.1 V-I colors. The B-V model colors from the ATLAS 9 grid are systematically redder below 4500 K. Below 4000 K, very large differences of several tenth of magnitude exist between all the model colors.

Similar comparisons (Lejeune et al., in prep.) for the dwarf models show that large deviations between the models and the BaSeL 3.1 empirical calibrations also exist, and are maximum below 4000 K. For the M dwarfs, model colors computed from the PHOENIX models provide the best agreement with the BaSeL 3.1 empirical calibrations.

4. Temperature-color calibrations

We also compared the theoretical temperature-color calibrations, $T_{\text{eff}}$-(U-B) and $T_{\text{eff}}$-(B-V), predicted by each grid of models in the range $3000K \leq T_{\text{eff}} \leq 6000K$, with the temperature scales adopted in BaSeL 3.1 and the empirical calibrations of Alonso et al (1998, 1999) derived from the IRFM method. Our results (Lejeune et al., in prep) show that, for $T_{\text{eff}} > 4000K$, the theoretical scales for all the
models agree well with the BaSeL 3.1 empirical relations for \([Fe/H] = 0.0\) and 
\([-2.0\). Surprisingly, below 4000 K the theoretical calibrations from ATLAS 9
model atmospheres are found in very good agreement with the empirical values.
The \(T_{\text{eff}}-(\text{B-V})\) relation from the NMARCS model colors for dwarfs deviates sig-
nificantly (more than 0.5 mag at \(T_{\text{eff}} = 3000K\)) from the BaSeL 3.1 empirical
calibrations, while the NextGen model calibrations are closer. For the giants, the
NMARCS models provide in general a better match to the empirical relations
than the NextGen models. Comparisons of the BaSeL 3.1 calibrations with the
metallicity-dependent temperature-color empirical relations of Alonso et al. in
the temperature range 7000 K – 4000 K show a good agreement (less than 0.05
mag) for the dwarf sequences, but a more significant discrepancy (> 0.1 mag in
average) for the giant sequence with \([Fe/H] = -2.0\).

5. Conclusions

UBVRI colors of the most widely used theoretical spectral libraries (ATLAS 9, 
PHOENIX, NMARCS, and BaSeL ) in the temperature range 7000 K – 3000 K
have been compared with empirical calibrations available for 
\(-2.0 \leq [Fe/H] \leq +0.5\). We found that the ATLAS 9 model colors from Castelli et al. (1997)
agree well or very well with the empirical color-temperature relations at all metallic-
ities and over the range of effective temperatures between 6000 K and 3500 K.
The most significant deviations are found for the \(T_{\text{eff}}-(U-B)\) relation at solar
metallicity. Below 4000 K, important deviations are found for the UBV col-
ors between both the PHOENIX NextGen and the NMARCS model predictions
with respect to the BaSeL 3.1 empirical relations, although some uncertainties
still exist in the empirical data at these low temperatures. In a general way,
the deviations appear to be less important with the PHOENIX NextGen model
colors for dwarfs, and with the NMARCS models for giants.

These differences have to be accounted for, or maybe reduced with some
spectral corrections methods, in the selection of models in order to construct a
spectral library well suitable to the definition of the GAIA photometric system.

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Figure 1. A comparison of the different grids of models with log $g=1$ in the (B-V)/(V-I) two-color diagram. Top panel: the BaSeL 2.2 and 3.1 model colors. Bottom panel: the ATLAS 9 (Castelli et al.), the PHOENIX and the NMARCS models. The lines connect the models with the same metallicity ($[Fe/H]=-0.6,-0.3$ and 0.0 (thick line), and the models with the same $T_{\text{eff}}$ as indicated in each panel. The models show very large differences in the M giant regime (see text).