Mem. S.A.It. Vol. 88, 90

Memorie della

Using CO5BOLD models to predict the effects of granulation on colours

P. Bonifacio[1], E. Caffau[1], H.-G. Ludwig[2,1], M. Steffen[3,1], F. Castelli[4], A.J. Gallagher[1], D. Prakapavičius[5], A. Kučinskas[5], R. Cayrel[1], B. Freytag[6], B. Plez[7], and D. Homeier[2]

[1] GEPI, Observatoire de Paris, PSL Research University, CNRS, Place Jules Janssen, 92195 Meudon, France
e-mail: Piercarlo.Bonifacio@obspm.fr
[2] Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany
[3] Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
[4] Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34131 Trieste, Italy
[5] Institute of Theoretical Physics and Astronomy, Vilnius University, Sauletekio 3, Vilnius LT-10222, Lithuania
[6] Department of Physics and Astronomy at Uppsala University, Regementsvägen 1, Box 516, 75120, Uppsala, Sweden
[7] LUPM, Université de Montpellier, CNRS, UMR 5299, 34095 Montpellier Cedex 05, France

Abstract. In order to investigate the effects of granulation on fluxes and colours, we computed the emerging fluxes from the models in the CO5BOLD grid with metallicities [M/H]=0.0,–1.0,–2.0 and –3.0. These fluxes have been used to compute colours in different photometric systems. We explain here how our computations have been performed and provide some results.

Key words. Convection – Hydrodynamics - Stars: atmospheres

1. Introduction

Colours and fluxes have a very important role in the study of stars and galaxies. In fact, the former provide most of the light emitted by the latter. A photometric study consists of measuring the photons that are emitted by an object in few selected spectral bands. Broad band photometry corresponds to a resolution $R = \lambda/\Delta\lambda \approx 6$. This low resolution can still convey very important information on the source if the bands are cleverly chosen. Since to obtain a photometric measurement one does not need to disperse the light, but merely to isolate the photons in the band, for a telescope of a given size, photometric measurements can reach much deeper (fainter magnitudes), than corresponding spectroscopic measurements. For this reason photometry is the primary means of investigating faint objects. It is therefore important to have a good comprehension of the photon flux emitted by the stars and understand, theoretically, how flux ratios, in selected bands (colours) depend on the star's main properties: effective temperature, surface gravity and chemical composition. While this problem has been thoroughly explored on the basis of one-dimensional, static, model atmospheres (e.g. Bessell et al. 1998; Castelli 1999; Önehag et al. 2009; Castelli & Kurucz 2006; Bessell & Murphy 2012; Casagrande & VandenBerg 2014), there is no systematic study of colours and fluxes on the basis of three-dimensional time-dependent hydrodynamical simulations. Colours from hydrodynamical simulations have been studied for two cases by Kučinskas et al. (2005) and Kučinskas et al. (2009). We decided to begin a systematic study using the CO5BOLD models from the CIFIST grid (Ludwig et al. 2009). To each CO5BOLD model we associate a 1D model computed with the LHD code (Caffau & Ludwig 2007), that uses the same opacities and microphysics as the CO5BOLD model. We report some of the results from this study here and explain our main assumptions.

2. Photometry: definitions and methods

2.1. Magnitudes and photometric systems

The definition of photometric systems has been often discussed in the literature and we refer the reader to the papers of Bessell (1990) and Bessell & Murphy (2012) that define the bandpasses for the *UBVRI* system, Bessell et al. (1998); Castelli (1999); Girardi et al. (2002); Casagrande & VandenBerg (2014) that deal with the problem of providing synthetic photometry, as well as to the recent review of Bohlin et al. (2014) on absolute flux calibration. However we want to define the problem in a way that remains close to the observational origin of photometry. Our approach to the problem is to start from the basic definition of magnitude m of a star in any heterochromatic[1] photometric system

$$m - m_0 = -2.5\log\left(\frac{\int f(\lambda)R(\lambda)d\lambda}{\int R(\lambda)d\lambda}\right) \quad (1)$$

where R is the bandpass (see e.g Bessell 1990, for a definition) f is the flux received at earth from the star and

$$m_0 = \text{constant} - 2.5\log\left(\frac{\int f_0(\lambda)R(\lambda)d\lambda}{\int R(\lambda)d\lambda}\right) \quad (2)$$

is the magnitude of a *standard star*. The constant in the above definition reflects the fact that one has one further degree of freedom: one may define the magnitude of the primary standard arbitrarily. A logical choice is to set the constant such that $m_0 = 0.0$, but one may also decide that magnitude zero corresponds to an arbitarily chosen flux F_{b0} in the band. In this case the magnitude of the primary standard is non-zero and equal to

$$m_0 = -2.5\log\left(\frac{F_{b0}}{\int R(\lambda)d\lambda}\right) - 2.5\log\left(\frac{\int f_0(\lambda)R(\lambda)d\lambda}{\int R(\lambda)d\lambda}\right) \quad (3)$$

There is a slight difference in defining magnitudes if one integrates over energy, like in equation 1 or if one counts photons, in which case a factor of λ would appear in the integrand both at the numerator and at the denominator (Bessell et al. 1998; Girardi et al. 2002; Casagrande & VandenBerg 2014).

$$m - m_0 = -2.5\log\left(\frac{\int \lambda f(\lambda)R(\lambda)d\lambda}{\int \lambda R(\lambda)d\lambda}\right) \quad (4)$$

Observationally whether one is performing energy integration or photon integration depends on the detector used and on its mode of operation. A photomultiplier tube can be operated in current integration mode, or in photon-counting mode. In the first case one is doing energy integration, in the second case photon integration. Solid state devices, like CCDs

[1] Consisting of different wavelengths or frequencies, as opposed to monochromatic.

and IR arrays can only be operated in photon-counting mode.

An heterochromatic system is equivalent to a monochromatic system (Brill 1938) provided we define the *isophotal wavelength* as:

$$\lambda_i = \frac{\int \lambda R(\lambda) d\lambda}{\int R(\lambda) d\lambda}. \tag{5}$$

We can then define a monochromatic flux density at the isophotal wavelength, f_{b0}, such that

$$F_{b0} = f_{b0} \int R(\lambda) d\lambda \tag{6}$$

For instance for the 2MASS system Cohen et al. (2003) provide in-band fluxes, isophotal wavelengths and fluxes for a zero magnitude object, in each of the 2MASS bands in their Table 2. These are close, but not equal to, the corresponding fluxes for Vega, as we shall se below, thus Vega has non-zero magnitudes in the 2MASS system. Also in the standardised Bessel *UBVRI* system (Bessell 1990), Vega has $V = 0.03$, not 0.00. In the AB magnitude system (Oke & Gunn 1983), one chooses zero magnitude for an object with a constant flux density of $f_\nu = 3.631 \times 10^{-23}\,\mathrm{W\,Hz^{-1}\,m^{-2}}$ for all ν. Note that previously we defined magnitudes in terms of f_λ, given that $c = \lambda\nu$, at 548 nm the above flux density corresponds to $\mathrm{f}_\lambda = 3.625 \times 10^{-11}\,\mathrm{W\,nm^{-1}\,m^{-2}}$. Oke & Gunn (1983) provided a set of standards for absolute spectrophotometry and introduced the AB magnitude, intended for a monochromatic system. The concept is easily generalised to an heterochromatic system using this flux density as isophotal flux density for any band.

In the following we shall refer to the star of magnitude m_0 as the *primary standard*. In theory it is sufficient to measure the flux of the standard star, by comparing its measured flux to a source of known flux, e.g. a laboratory black-body, to completely define the magnitude system. In practice when observing, a photometric system is defined by a set of standard stars, that are observed with the same instrumentation. The basic concepts of calibrating stellar photometry is well described in Harris et al. (1981). The crucial point, however, is that all standard stars must be tied to the primary standard. Once the magnitude of the primary standard is fixed (arbitrarily), then the magnitudes of all other standards are also fixed by equation 1.

So far we have only discussed magnitudes in a specific bandpass, however, one usually uses a multi-colour photometric system with several bandpasses. One has to therefore define the constant that fixes magnitude zero for each bandpass in equation 2. Historically, the first choice has been to fix $m_0 = 0.0$ for the primary standard in all band passes and the primary standard is, or may be tied to, Vega. This choice is handy for stellar work, since then Vega has a colour zero for any pair of bands and it is immediately clear whether the star is “redder” or “bluer” than Vega. One should underline that Vega, like Sirius, has always been considered as a prototypical star of spectral type A0. Multi-colour systems that make this choice are usually referred to as “Vega” systems. Johnson, Strömgren, Geneva, Vilnius, 2MASS systems are all of this type. The SDSS *ugriz* system is an AB system. Note that even if f_ν is constant with frequency or wavelength, f_λ is not, given the inverse relation between frequency and wavelength. Note also that even an AB system like *ugriz* is not independent of the absolute calibration of Vega. In fact the system relies on four spectrophotometric standard stars (Fukugita et al. 1996), whose flux has been tied to the absolute flux of Vega. In fact the difference between “Vega” and AB systems is simply on how the constant in equation 2 is defined for the different bandpasses of the system.

2.2. Establishing standard stars

The traditional approach is to observe the standard stars and the “program” stars with the same equipment. The data reduction method described in Harris et al. (1981) for photoelectric photometry can also be easily generalised for different detectors. In substance, using the observations of the standard stars, one transforms the raw counts to magnitudes in the “standard” system. However, when observing with medium size telescopes, the traditional primary standards, like Vega, are too bright to be observed, thus the observations have to rely on fainter "secondary standards". The strategy to make sure that the observations based on secondary standards are on the same system as the primary is to observe the primary and secondary standards with a smaller telescope. An elegant way to tackle the problem is that used by 2MASS (Cohen et al. 2003). The first step is to accurately measure the bandpasses of the system. Then use an absolutely calibrated spectrum of Vega, to integrate through these bandpasses and obtain in-band fluxes and flux densities at the isophotal wavelength for each band, and define the fluxes of the zero-magnitude object with respect to these fluxes. Although the primary standard is not observed through the same equipment, one ties the measurements to it. A similar approach has also been adopted by SDSS; the spectrophotometry of the four primary standards has been multiplied by the bandpass and integrated over the band. This allows one to establish the magnitude of each star, in each band, knowing that, as mentioned above, magnitude zero corresponds to a flux density of $f_\nu = 3.631 \times 10^{-23} \mathrm{WHz^{-1}m^{-2}}$.

2.3. Synthetic photometry

Synthetic photometry is defined as the computation of colours and magnitudes from a set of model atmospheres. The first thing to keep in mind is that from a model atmosphere one can compute the emergent flux per unit surface. To compare this flux to that observed from a star, one has to multiply the flux by the square of the angular radius [2] of the star and correct the observed flux for the effect of interstellar extinction. On the other hand, colours can be computed directly from the fluxes per unit surface at the stellar surface. The classical approach for obtaining colours and magnitudes on a standard photometric system is well described in Castelli (1999). One uses a model atmosphere of a primary standard star (Vega) and then adds zero points to colours and magnitudes so as to force the theoretical magnitudes and colours to be equal to the observed colours of the primary standard. An alternative approach is that described by Casagrande & VandenBerg (2014). One assumes a distance and a radius and then treats the theoretical flux exactly as if it were an observed flux. The advantage of the first approach is that since all magnitudes and colours are computed with respect to a theoretical flux, one may hope that a part of the systematical errors in the theoretical fluxes will cancel out. The advantage of the second approach is that one does not need to model precisely the flux of the primary standard, as we shall see in the case of Vega this is indeed difficult.

For the $UBVRI$ and other "classical" systems it has been customary, in observations, to provide one magnitude and several colours. This practice can be understood by considering that for ground based observations a large part of the uncertainty comes from the atmospheric extinction. While atmospheric extinction in any band can vary considerably from night to night or even within the same night, the ratio of extinction in two bands is a lot less variable. This means that one may obtain accurate colours (but not magnitudes) even under non-photometric conditions. For more modern systems, like 2MASS it has become customary to provide the absolute flux calibration of each band, instead.

Whichever approach one wants to use in order to obtain theoretical colours and magnitudes on a "Vega" system, one still needs to assume a flux distribution for the primary standard and a set of magnitudes or colours for it.

2.4. The CALSPEC fluxes of Vega and Sirius

The Space Telescope Science Institute maintains the CALSPEC calibration database[3] that contains the stellar spectra that are flux standards for the Hubble Space Telescope. It is probably the best database of stellar fluxes currently available. Bohlin (2014) has presented

[2] For a star of radius R at a distance d the angular radius is $\theta/2 = R/d$

[3] `http://www.stsci.edu/hst/observatory/crds/calspec.html`

the latest version of absolute fluxes for Sirius and Vega. This is the result of an effort spanning over twenty years and makes use of many space observations. These fluxes are not "primary", but are tied to the fluxes of three white dwarfs that are considered as primary flux calibrators. Two things must be noted concerning Vega. Firstly, it is a fast rotator seen pole-on (Aufdenberg et al. 2006). This means that no "standard" model atmosphere may describe it accurately. Secondly, Vega is surrounded by dust rings, that provide an IR excess above what can be predicted by a model of its photosphere. For this reason the CALSPEC flux in the IR is just a theoretical flux. These two facts do not diminish the value of Vega as a flux standard, but seriously limit our ability to model it with "standard" models. Sirius does not present any of such problems, and for this reason seems to be a more desirable standard.

We integrated the CALSPEC spectra through the bandpasses of the $UBVRI$ system and the Hipparcos H_p, B_T, V, T system as defined by Bessell & Murphy (2012) as well as the JHK_S 2MASS (Cohen et al. 2003), in order to establish the zero points. We followed Bessell & Murphy (2012) and forced all the $UBVRI$, H_p, B_T, V, T to be equal to 0.03 for Vega. In the same spirit for the Gaia bandpasses[4] we assumed G,BP,RP,RVS to be equal to 0.03. In Table 1 we assemble the $UBVRI$ data for Vega and Sirius, taken from Table A1 of Bessell et al. (1998). For the JHK_S magnitudes we computed the in-band flux and computed the magnitude for Vega using the zero-magnitude in-band fluxes of Cohen et al. (2003), these fluxes and magnitudes are given in Table 2.

We used the above data for Vega, to fix the constant in equation 2, and then compute the colours and magnitudes for Sirius from the CALSPEC spectrum and apply the additional zero points in Table 3 of Bessell & Murphy (2012) we obtain: $V = -1.430$, $U-B = -0.062$, $B-V = -0.005$, $V-R = -0.018$, $V-I = -0.039$. This means that in some cases the colours and magnitudes of Sirius are off by over 0.01 mag with respect to the "standard" values. The relative systematic error estimated for the CALSPEC spectra is 1%, thus these differences are well within $1\,\sigma$ error on either side. We do not expect the magnitude of any other "standard" star to be known better than either Sirius or Vega. Thus, the absolute error on the magnitude of any standard star is not expected to be known to better than 0.01 mag. This implies that this is almost the ultimate accuracy of any magnitude or colour. This remark also affects AB magnitudes, like *ugriz*, since as pointed out before, they are also tied to the absolute calibration of Vega, via the spectrophotometry of the primary standards.

To compute the synthetic magnitudes for the Vega systems we decided to use the approach of Casagrande & VandenBerg (2014), i.e. adopt a radius of one solar radius for each model atmosphere at distance of 10 pc. This amounts to multiplying the fluxes per unit surface computed from the stellar atmosphere by a factor $(R_\odot/10)^2 = 5.083267\times10^{-18}$, where the solar radius is expressed in pc. We made this choice for two reasons: firstly, we cannot compute a model for Vega (or Sirius) with CO5BOLD, secondly, even if we could rely on an LHD model, the opacity used would be different from that used in the CO5BOLD models, because of the peculiar chemical composition of Vega (Castelli & Kurucz 1994). Using Sirius as a standard does not relieve the problem, since it has a peculiar chemical composition (Landstreet 2011) and would need an "ad hoc" model that would be different from the other models in the grid. On top of this the opacity used in the CO5BOLD models in the CIFIST grid is derived from that of a 1D MARCS model atmosphere, and the MARCS models do not exceed 8000 K (Gustafsson et al. 2008). Thus any LHD model we could compute for Vega or Sirius would be significantly different from those in the CIFIST grid.

3. Computation of fluxes from model atmospheres

Starting from a model atmosphere, computing the emergent flux simply requires an integra-

[4] http://www.cosmos.esa.int/documents/29201/302420/normalisedPassbands.txt/a65b04bd-4060-44fa-be36-91975f2bd58a

Table 1. *UBVRI* data for Vega and Sirius, compiled by Bessell et al. (1998)

Star	V	$U-B$	$B-V$	$V-R$	$V-I$
Vega	0.030	0.000	–0.010	–0.009	–0.005
Sirius	–1.430	–0.045	–0.000	–0.010	–0.016

Table 2. 2MASS in-band fluxes and corresponding magnitudes from Cohen et al. (2003)

Star	FJ Wcm^{-2} $\times 10^{-14}$	J mag	FH Wcm^{-2} $\times 10^{-14}$	H mag	FK_S Wcm^{-2} $\times 10^{-14}$	K_S mag
Vega	5.076	0.000	2.857	–0.005	1.121	0.001
Sirius	18.500	–1.404	10.274	–1.395	4.007	–1.382
0 mag	5.082	0.000	2.843	0.000	1.122	0.000

tion of the radiative transfer equation. While this is straightforward for a 1D static model atmosphere, it becomes very computational demanding in a 3D hydrodynamical model atmosphere. This problem is solved in an elegant way in the NLTE3D code (Steffen et al. 2015), that requires the computation of the radiation field for computing the photoionization rates. The solution is to account for the line opacity by using the ATLAS opacity distribution functions (ODFs) (Castelli & Kurucz 2003), while the continuum opacities are provided by the Linfor3D IONOPA package (see Steffen et al. 2015; Ludwig & Steffen 2013, for details). The advantage is that the ATLAS ODFs use a small, but manageable, set of frequencies (1212 for the LITTLE ODFs) compared to the CO5BOLD opacity files that usually contain 5 to 12 opacity bins. The ODFs that we use, both for the computation of the CO5BOLD and LHD fluxes and for the ATLAS models and fluxes differ from those of Castelli & Kurucz (2003), in that they were recomputed by F. Castelli using a new release of the H_2O line lists[5]. This only impacts the models with effective temperatures below 4500,K. It can be noted that at low temperatures, colours and magnitudes derived from the ATLAS models computed for this project do not lie on the curves defined by the Castelli & Kurucz (2003) grid.

Two main differences apply here with respect to the NLTE computations of Steffen et al. (2015): we use the LITTLE ODFs, with 1212 wavelength bins (see Castelli 2005, for details on the ATLAS ODFs), we start the computation at shorter wavelengths, in fact at bin 165, corresponding to 133.5 nm. The latter should ensure that our fluxes are also usable for near UV colours. We are aware that this method is inconsistent, in the sense that the opacity that is used in the flux computation is different from the opacity that has been used in the model computation. However this approach greatly simplifies the computation.

Like in Steffen et al. (2015) we have treated scattering as true absorption. For each model in the grid we select a series of snapshots (typically twenty) that constitute a representative statistical ensemble of the model. For each snapshot NLTE3D provides the emerging intensities for five inclinations μ. There is another slight inconsistency here, since the CO5BOLD models we use are computed with only three values of μ. The emerging flux is then computed by integrating over angles, using a Lobatto integration scheme (Davis & Polonsky 1972). The resulting fluxes from each snapshot are then averaged to provide the time averaged emerging flux. We performed these computations on an inhomogeneous Linux based computer cluster at the Observatoire de Paris. The computation was done in an "embarrassingly parallel" way, each snapshot running on a different compute core. We were able to get several tens of cores running at any given time. Each job took about 24h to complete. The com-

[5] http://kurucz.harvard.edu/molecules/h2o/h2ofastfix.readme

putation of fluxes for the whole grid (comprising 111 models that cover the metallicity range $0.0 \leq [M/H] \leq -3.0$, temperature range 3800 K to 6800 K and surface gravity $1.0 \leq \log g \leq 4.5$. took about six months.

For the LHD models we used the same code and approximations, of course the computations wer much faster. For the ATLAS models the emerging fluxes were computed directly using the ATLAS code.

4. From fluxes to colours

Since all the flux computations are based on the ATLAS ODFs, all the computed fluxes are provided for the same set of wavelength bins. This is handy because we can use the same computer program to compute the colours from any set of model atmospheres. We used a modified version of the colour programs by R. Kurucz (Kurucz 2016). For the *UBVRI* system, the defining standard stars were originally observed with photomultipliers operated in current integration mode (see Bessell 1990; Bessell et al. 1998). Therefore, we used equation 1 to compute the *UBVRI* colours. We did the same for the Hipparcos, Tycho and Gaia photometry, that is closely tied to the classical *BV* photometry.

We compute also bolometric corrections for the V band and for the Hipparcos H_p. To do so we use the same approach as Casagrande & VandenBerg (2014). Having decided to scale all our theoretical fluxes for one solar radius and placing them at 10 pc the absolute bolometric magnitude corresponding to each model is:

$$M_{\rm Bol} = -2.5 \log\left(T^4/T_\odot^4\right) + M_{\rm Bol\,\odot} \quad (7)$$

where T and $T_\odot$ are the effective temperatures of the model and the Sun respectively. To set the zero point of the absolute magnitudes the International Astronomical Union in the XXIXth General Assembly in Honolulu, passed Resolution 2015 B2[6], that implies $M_{\rm Bol\,\odot} = 4.74$.

[6] https://www.iau.org/static/resolutions/IAU2015_English.pdf

This leads to the bolometric corrections

$$BCV = M_{\rm Bol} - M_V \quad (8)$$

$$BCHP = M_{\rm Bol} - M_{H_p} \quad (9)$$

$$BCG = M_{\rm Bol} - M_G \quad (10)$$

Note that this choice may imply that some of the bolometric corrections are positive. Although this may appear counterintuitive it is a natural consequence of this choice for the zero point.

For the SDSS system we preferred to use a photon counting approach. A further complication is that the SDSS catalog does not provide magnitudes, but "luptitudes" defined in Lupton et al. (1999) as

$$m = -\frac{2.5}{\ln(10)}\left[\operatorname{asinh}\left((f/f_0)/(2b)\right) + \ln(b)\right] \quad (11)$$

where f_0 is the flux of the zero magnitude object like in equation 2 and b is a constant called "softening parameter". The main advantage of this definition is that even if f vanishes (we have an upper limit on the object's flux) the magnitude is defined and has a finite value, while for the traditional Pogson formula the magnitude diverges. The softening parameter is chosen so that this finite value corresponds to the limiting magnitude of the survey. For SDSS the b values of the various bands are of the order of 10^{-10}. SDSS is an AB system and the zero magnitude object is the constant f_ν as defined above. Luptitudes and magnitudes differ by less than 1% for all fluxes that are larger than $10 f_0 b$, for example, for g this means $g < 22.60$. As pointed out by Girardi et al. (2004) it is impossible to define a bolometric correction in a simple way using luptitudes, they therefore decided to compute magnitudes with the SDSS filters. We chose a different approach, we compute luptitudes, that should be directly comparable to colours in the SDSS catalog, we want to make sure that we are not introducing any systematic error in our synthetic colours. We do not provide bolometric corrections for the SDSS filters, but only colours.

We would like to point out that there is an increasing number of "Sloan-like" surveys that are carried out with Sloan-like filters, or

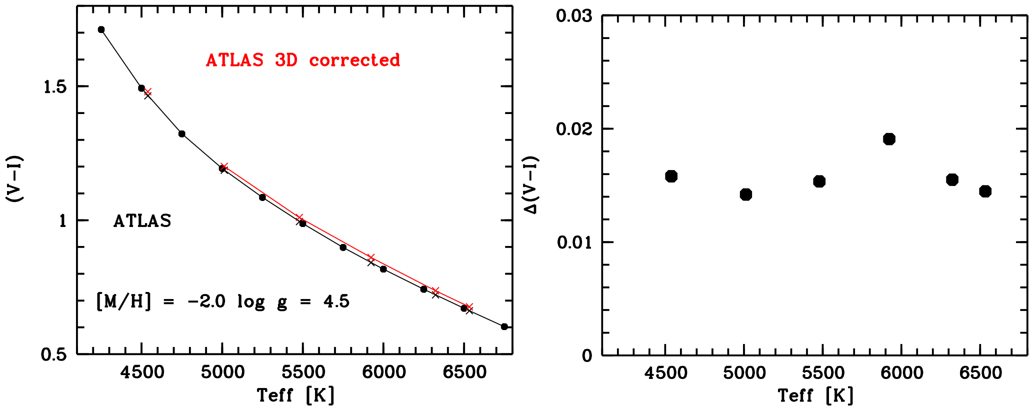

Fig. 1. Left panel: the $V - I$ colour as a function of $T_{\rm eff}$ for the models of metallicity –2.0 and log g=4.5. Black are ATLAS models, dots are the models from the Castelli & Kurucz (2003) grid, crosses are the models computed for this project, with the same prescriptions as the Castelli & Kurucz (2003) grid. Red are the colours from the ATLAS models to which we added the 3D correction. Right panel: the 3D corrections on the $V - I$ colour for the same models.

a subset of them, on a variety of telescopes that provide magnitudes rather than luptitudes. In principle all of these are designed to be close to SDSS, and often rely on SDSS secondary standards for their calibration. Yet in some cases the filters are significantly different from the original SDSS filters, and if one wishes to provide accurate synthetic photometry for these surveys it would be preferable to compute it with the appropriate filters and also with the magnitude definition adopted for any given survey. A cross-calibration of several of these surveys onto a single Sloan-like homogeneized system has not yet been attempted.

5. Results

The CIFIST grid is coarse, with respect to existing grids of 1D model atmospheres. Our approach is to compute a 3D correction defined as: C = X(3D) - X(LHD), for each colour or magnitude X. Then for our reference ATLAS model, that has the same effective temperature, surface gravity and metallicity as our CO5BOLD and LHD model we compute the corrected X as X_c=X(ATLAS)+ C.

The result of this exercise is displayed in Fig. 1. For the set of models with metallicity –2.0 and log g=4.5 we show the $V - I$ colour as a function of effective temperature. This colour measures the slope of the Paschen continuum and is very often used as temperature indicator. The black symbols are the colours computed from the ATLAS models, the red symbols are the colours after the 3D correction. For temperatures below 5000 K the correction is vanishingly small, but above the correction is small, though non-negligible. If we were to estimate the effective temperature from an observed $V - I$ colour using the red curve we would derive a temperature that is about 50 K to 100 K hotter than if we used the black curve. Another feature that is obvious from Fig. 1 is that both colours and 3D corrections are smooth functions of the main stellar parameters, like $T_{\rm eff}$. This makes it possible to use a coarse grid of 3D models, like the CIFIST grid, to determine the 3D corrections for a much denser grid of 1D models.

In Fig. 2 we show the bolometric correction in the Gaia G band from the ATLAS models (black symbols and lines) and the 3D-corrected values (red symbols) as a function of $T_{\rm eff}$. The 3D-corrections are generally very small, but note, at solar metallicity, how they increase with increasing effective temperature, reaching the largest correction (in absolute value) for our hottest model. Given that the mean temperature structure of the CO5BOLD models at solar metallicity is very close to that of the corre-

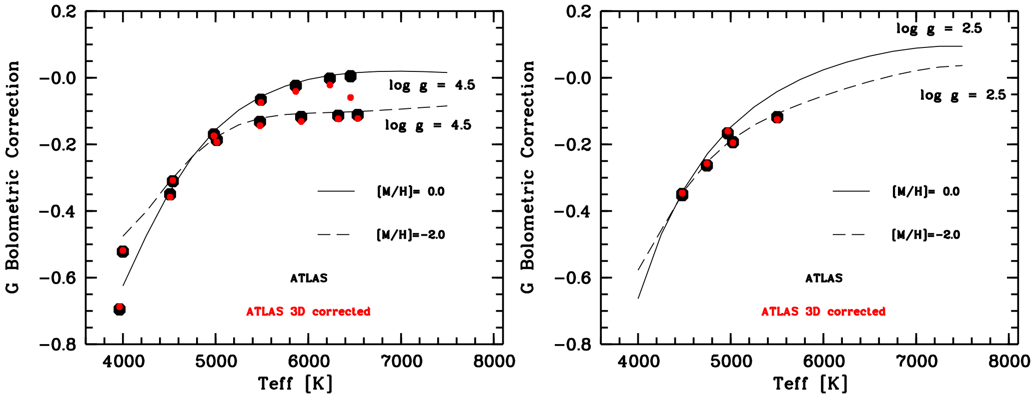

Fig. 2. Bolometric corrections in the Gaia G band for four sets of models: log g = 2.5 (right panel) and log = 4.5 (left panel) at [M/H]=+0.0 and [M/H]=–2.0. Black symbols are computed from our ATLAS models, the lines are the bolometric corrections computed from the Castelli & Kurucz (2003) grid. The solid line refers to models of solar metallicity, the dashed line to models with metallicity –2.0. The red symbols are the values to which we added the 3D correction.

sponding LHD model we attribute this effect to the role of the temperature fluctuations, that become more important for hotter models.

6. Conclusions

We have presented our methods for computing fluxes and colours from CO5BOLD models. We use these fluxes to derive 3D-corrections that can be applied to any grid of colours computed from 1D models. In considering our results one has to keep in mind the approximations that we have made, and the limitations of our models. In our opinion the main shortcoming of our computations is the fact that we treated scattering as true absorption both in the computation of the models and of the emerging fluxes. The importance of this is fully addressed in the accompanying paper Bonifacio et al. (2017). We consider this first attempt at the study of the effects of granulations on fluxes and colours as exploratory.

Acknowledgements. This project has been supported by fondation MERAC and Observatoire de Paris. We acknowledge financial support from CNRS Institut National de Sciences de l'Univers, Programme National de Cosmologie et Galaxies and Programme National de Physique Stellaire. This work was granted access to the HPC resources of MesoPSL financed by the Région Île de France and the project Equip@Meso (reference ANR-10-EQPX-29-01) of the programme Investissements d'Avenir supervised by the Agence Nationale pour la Recherche. This work was supported by grant from the Research Council of Lithuania (MIP-089/2015).

References

Aufdenberg, J. P., Mérand, A., Coudé du Foresto, V., et al. 2006, ApJ, 645, 664
Bessell, M. S. 1990, PASP, 102, 1181
Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Bessell, M., & Murphy, S. 2012, PASP, 124, 140
Bohlin, R. C. 2014, AJ, 147, 127
Bohlin, R. C., Gordon, K. D., & Tremblay, P.-E. 2014, PASP, 126, 711
Bonifacio, P., Caffau, E., Ludwig, H.-G. et al. 2017, A&A, submitted
Brill, A. 1938, ZAp, 15, 137
Caffau, E., & Ludwig, H.-G. 2007, A&A, 467, L11
Casagrande, L., & VandenBerg, D. A. 2014, MNRAS, 444, 392
Castelli, F. 1999, A&A, 346, 564
Castelli, F. 2005, MSAIS, 8, 34
Castelli, F., & Kurucz, R. L. 1994, A&A, 281, 817

Castelli, F. & Kurucz, R. L. 2003, in Modelling of Stellar Atmospheres, ed. N. Piskunov, W. W. Weiss, & D. F. Gray (ASP, San Francisco), IAU Symp., 210, poster A20

Castelli, F., & Kurucz, R. L. 2006, A&A, 454, 333

Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, AJ, 126, 1090

Davis P. J. & Polonsky I. 1972, in Handbook of Mathematical Functions, ed. M. Abramowitz, & I. A. Stegun (Dover Publ., New York), 877

Freytag, B., Steffen, M., Ludwig, H.-G., et al. 2012, J. Comp. Phys., 231, 919

Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748

Girardi, L., Bertelli, G., Bressan, A., et al. 2002, A&A, 391, 195

Girardi, L., Grebel, E. K., Odenkirchen, M., & Chiosi, C. 2004, A&A, 422, 205

Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951

Harris, W. E., Fitzgerald, M. P., & Reed, B. C. 1981, PASP, 93, 507

Kučinskas, A., Hauschildt, P. H., Ludwig, H.-G., et al. 2005, A&A, 442, 281

Kučinskas, A., Ludwig, H.-G., Caffau, E., & Steffen, M. 2009, MmSAI, 80, 723

Kurucz, R. L. 2005, MSAIS, 8, 14

Kurucz, R. L. 2016, Listing of programs retrieved on July 1 2016, `http://kurucz.harvard.edu/programs/colors/`

Landstreet, J. D. 2011, A&A, 528, A132

Ludwig, H.-G., Caffau, E., Steffen, M., et al. 2009, MmSAI, 80, 711

Ludwig, H.-G., & Steffen, M. 2013, MSAIS, 24, 53

Lupton, R. H., Gunn, J. E., & Szalay, A. S. 1999, AJ, 118, 1406

Önehag, A., Gustafsson, B., Eriksson, K., & Edvardsson, B. 2009, A&A, 498, 527

Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713

Steffen, M., Prakapavičius, D., Caffau, E., et al. 2015, A&A, 583, A57