THEORETICAL MODELLING OF LATE-TYPE GIANT ATMOSPHERES: PREPARING FOR GAIA

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ABSTRACT

Late-type giants (RGB/AGB stars) will be important tracers of the Galactic morphology and evolution in the framework of Gaia, as they are intrinsically bright and thus can probe distant stellar populations or those obscured by interstellar extinction. A realistic representation of their atmospheres and spectra with stellar atmosphere models is thus of crucial importance, both for the design and optimization of Gaia instruments, as well as the interpretation of provided astrophysical data. Our analysis of synthetic photometric colours of late-type giants based on `PHOENIX`, `MARCS` and `ATLAS` model atmospheres indicates a general agreement between the current theoretical predictions and observations in the framework of stationary 1-D model atmospheres. Presently available models allow temperature determinations of RGB/AGB stars to an accuracy of $\sim \pm 100$ K. In an exploratory study we try to quantify possible residual systematic effects due to the approximations made in 1-D models using full 3-D hydrodynamical models. We find that differences in broad-band photometric colours calculated with 1-D and 3-D models are significant, translating to the offsets in effective temperature of up to $\Delta T_{\rm eff} \sim 70$ K. Clearly, full 3-D hydrodynamical models will help to alleviate such ambiguities in current theoretical modelling. Additionally, they will allow to study new phenomena, to open qualitatively new windows for stellar astrophysics in the Gaia-era.

Key words: Gaia; Photometry; Hydrodynamics.

1. IMPORTANCE OF LATE-TYPE GIANTS IN THE CONTEXT OF GAIA

Gaia will be an excellent instrument for studying Galactic stellar populations, especially in terms of their detailed formation histories, as it will provide parallaxes, proper motions, radial velocities, and astrophysical parameters (effective temperatures, metallicities, gravities and reddenings) for stars down to Gaia magnitude $G = 20$, which translates to Johnson $V \sim 21$ for $V-I = 2.0$ (or $T_{\rm eff} \sim 3700$ K) and $V \sim 20.5$ for $V-I = 1.0$ ($T_{\rm eff} \sim 4800$ K). This unique combination of kinematical and astrophysical information which is not accessible otherwise will provide an opportunity to investigate formation and evolution of the Galaxy in unprecedented detail.

Currently stellar populations are predominantly dated using the main-sequence turn-off point (MSTO) stars which is the most reliable method among those available today. This requires precise photometry of typically faint main-sequence stars, i.e., those located at least one magnitude below the MSTO (at 15 Gyr and solar metallicity the MSTO is at $M_V \sim +4.6$). Moreover, photometric data should be obtained for a statistically sufficient number of stars in a given target population. Surprisingly, these two requirements appear to be rather demanding in the context of Gaia, since already a mild extinction in the galactic disc of e.g. $A_V \sim 0.7$ mag/kpc will make MSTO stars too faint to be detected with Gaia at rather short distances. The limiting distance to which stellar populations can be dated with Gaia using MSTO stars will vary depending on the number of MSTO stars, interstellar extinction, and other factors, but it will be generally confined to 2.0–2.5 kpc (Bertelli 2002). Clearly, unless other suitable and reliable tracers can be identified, the capability of Gaia for dating stellar populations will be restricted to a few kiloparsec within the solar neighbourhood. Late-type giants on the RGB and early-AGB can be very useful in overcoming this limitation. Being significantly brighter than MSTO stars they can be easily observed to large distances (at solar metallicity the absolute magnitude of a typical RGB star located ~ 1.5 mag below the RGB tip is $M_V \sim +0.5$). Hence, late-type giants will be extensively employed in the Gaia data analysis as they can provide information about distant stellar populations not accessible by using fainter main-sequence stars.

Until now, however, late-type giants have been scarcely used for dating stellar populations. Firstly, the observational scatter in their photometric colours is typically large compared to the spread of isochrones corresponding to different ages on the RGB/AGB, thus uncertainties in derived ages are large. Secondly, the evolution on the RGB/AGB is still rather uncertain, as theoretical models are dependent on a number of poorly constrained modelling parameters such as the mixing-length parameter and mass loss rate.

However, for Gaia there is evidence that effective temperature determinations of late-type giants may be feasible at an accuracy level of 1–2%, mostly from medium-band photometry (see Jordi & Høg, this volume). The quoted error level corresponds to the formal error resulting from the fitting procedure with theoretical model atmospheres. At least for some stars the medium-band photometry will be supplemented by ground-based data obtained by massive future spectroscopic (e.g., RAVE) and photometric (e.g., VST, VISTA, UKIDSS) surveys. Near-infrared photometry will be especially important in this context, as it will allow us to put even tighter constrains on the effective temperatures (see Kučinskas et al. 2003, hereafter K03) and interstellar extinction. This will allow us to obtain sufficiently precise astrophysical parameters of RGB/AGB stars ($\sigma(T_{\rm eff}) \sim$ 50–100 K, see Section 2), which, in turn, may provide age estimates at an (formal) accuracy level of $\sim$ 20% or better.

The most essential ingredient missing here today is the availability of reliable evolutionary models, which would provide a solid basis for precise and unambiguous dating of stellar populations with RGB/AGB stars. At least partly this is due to the inadequate treatment of multi-dimensional phenomena (especially convection) within the classical 1-D models. It is conceivable that at least some of these problems will be solved with full 3–D hydrodynamical models, which may be available for routine use within $\sim$10 years from now. Being constructed to account for time-dependent and non-spherical phenomena, 3-D hydrodynamical models may help to alleviate the majority of ambiguities in theoretical modelling of stellar evolution on the RGB/AGB (especially those related with convection, mass-loss, pulsations, etc).

2. CURRENT STATUS IN THEORETICAL MODELLING OF LATE-TYPE GIANT ATMOSPHERES: SYNTHETIC BROAD-BAND PHOTOMETRIC COLOURS

Clearly, a number of issues related to stellar evolution on the RGB/AGB have to be clarified before late-type giants can be widely used for reliable dating of stellar populations. Can today's theoretical model atmospheres provide a sufficient backup to obtain precise astrophysical parameters of individual giants from observations, in particular broad-band photometry?

To address this question we have performed an extensive comparison of synthetic broad-band photometric colours of late-type giants with observations, covering a wide range of effective temperatures, gravities and metallicities ($T_{\rm eff}$= 3000–4500 K, $\log g$= 0.5–2.5 and $[M/H]$= 0,$-$1.0,$-$2.0). Synthetic spectra used for this purpose were produced with the most recent versions of `PHOENIX`, `MARCS` and `ATLAS` model atmospheres (for details see: `PHOENIX`: Brott & Hauschildt, this volume; `MARCS`: Plez 2003; `ATLAS`: Castelli & Kurucz, 2003). Synthetic colours were calculated in the Johnson-Cousins-Glass system, using filter definitions from Bessell (1990) for the Johnson-Cousins *BVI* bands and from Bessell & Brett (1988) for Johnson-Glass *JK* bands. A carefully selected sample of local late-type giants with $T_{\rm eff}$ $<$ 5000 K was used for this comparison, with precise determinations of effective temperature available from interferometry (errors in $T_{\rm eff}$ typically below 5%). We also made sure that stars in this sample are non-peculiar (chemically or otherwise) and non-variable. Comparisons were made in $T_{\rm eff} - {\rm colour}$ and colour$-$colour planes, with synthetic photometric colours plotted according to a $T_{\rm eff} - \log g$ relation of Houdashelt et al. (2000). We included several commonly used $T_{\rm eff} - {\rm colour}$ relations in this analysis too (Figure 1). Here we present some results for solar metallicity; a full discussion covering also sub-solar metallicities will be given elsewhere (Kučinskas et al. 2005, A&A, in preparation).

Figure 1 shows that there is a general agreement between the synthetic broad-band colours predicted by today's stationary 1-D model atmospheres and the observations, especially in the $T_{\rm eff} - (V-K)$ and $T_{\rm eff} - (J-K)$ planes. Moreover, there is a remarkable agreement among the synthetic colours calculated with different stellar atmosphere models, translating typically into an uncertainty in $T_{\rm eff}$ of ±50 K over a large range of effective temperatures, gravities and metallicities. This indicates that presently available models may allow us to obtain effective temperatures of late-type giants with a precision of $\sim$ ±100 K, using a single broad-band photometric index like $V-I$, or $V-K$. The accuracy can still be improved if optical and near-infrared broad-band fluxes (such as Johnson's *BVRIJHK*) are fitted simultaneously with synthetic fluxes to obtain an estimate of $T_{\rm eff}$ (K03). Typically, observed fluxes at 5–6 wavelength points are sufficient to achieve a formal fitting accuracy (standard deviation) of $\sigma(T_{\rm eff}) \sim$ 50 K. This considerably reduces the observational scatter on the RGB/AGB, allowing to obtain ages with a precision of at least ±20% (see K03 for an example with LMC/SMS clusters).

3. TOWARDS HIGHER ACCURACY: FULL 3-D HYDRODYNAMICAL MODEL ATMOSPHERES

We conducted an exploratory study (Ludwig et al. 2005, in preparation) to estimate systematic effects on broad-band colours related to changes of the mean temperature profile and the presence of temperature inhomogeneities in a fully time-dependent 3-D hydrodynamical model atmosphere relative to a 1-D standard one. We considered a prototypical late-type giant with $T_{\rm eff}$ = 3700 K, $\log g$ = 1.0, $[M/H]$ = 0. It is an interesting example since standard models predict that convection is restricted to the optically thick layers, hence has no influence on the atmospheric structure and consequently on the spec-

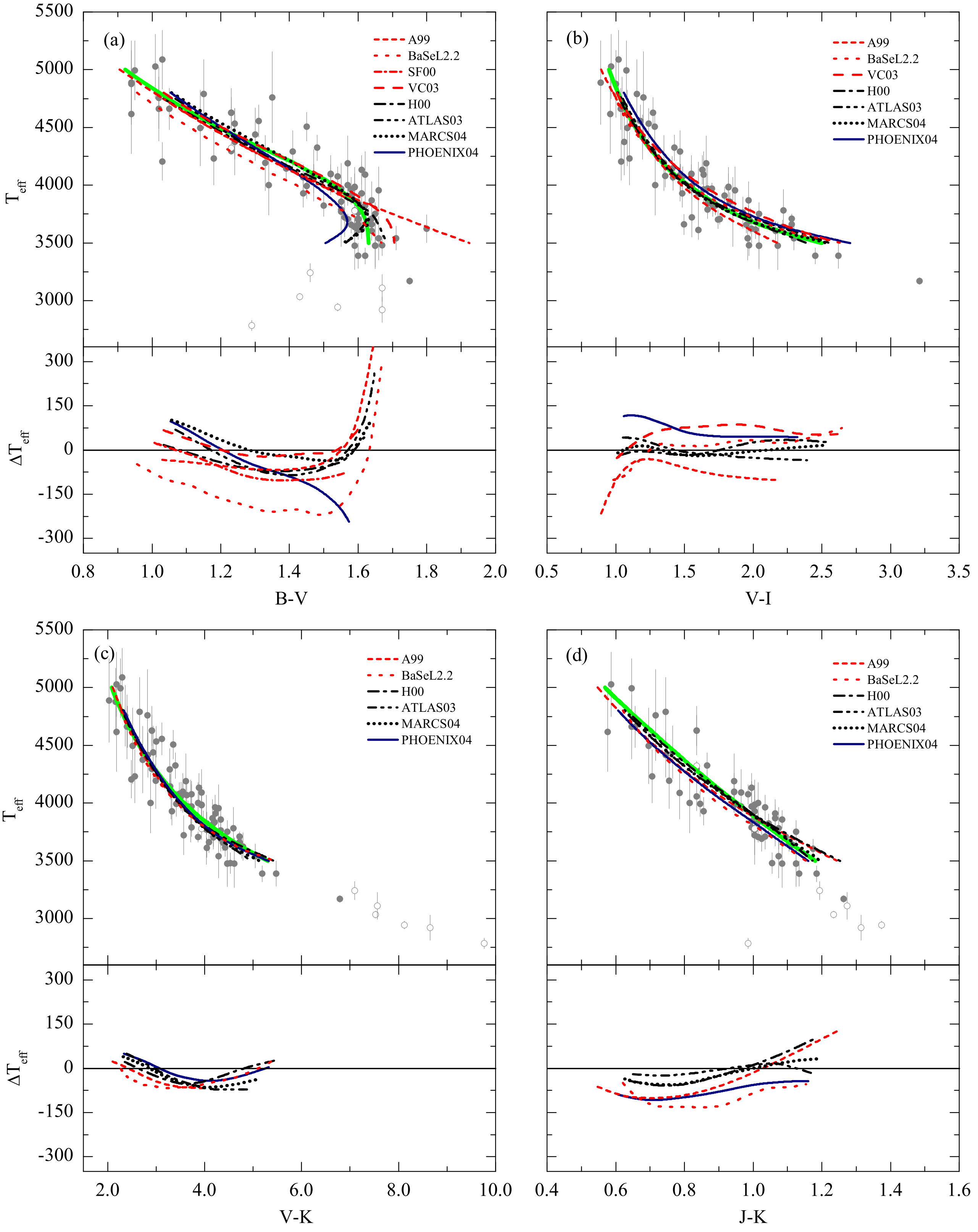

Figure 1. Empirical and theoretical $T_{\rm eff}$ − colour *relations for late-type giants in different* $T_{\rm eff}$ − colour *planes (a-d, top panels). Filled circles are non-variable late-type giants, several semiregular variables are highlighted as open circles. Thick solid line is a best-fit to the observed colours in a given* $T_{\rm eff}$ − colour *plane. Several existing* $T_{\rm eff}$ − colour *relations are shown as well, together with* $T_{\rm eff}$ − colour *scales constructed using synthetic colours of* `PHOENIX`, `MARCS` *and* `ATLAS` *(see text for details). Bottom panels in each figure show the difference between various* $T_{\rm eff}$ − colour *relations and the best fit to the observed data in a given* $T_{\rm eff}$ − colour *plane* ($\Delta T_{\rm eff} = T_{\rm eff}^{\rm other} - T_{\rm eff}^{\rm bestfit}$)*. Key to the legend: A99: Alonso et al. 1999; BaSel2.2: Lejeune et al. 1998; SF00: Sekiguchi & Fukugita 2000; VC03: Vandenberg & Clem 2003; H00: Houdashelt et al. 2000*

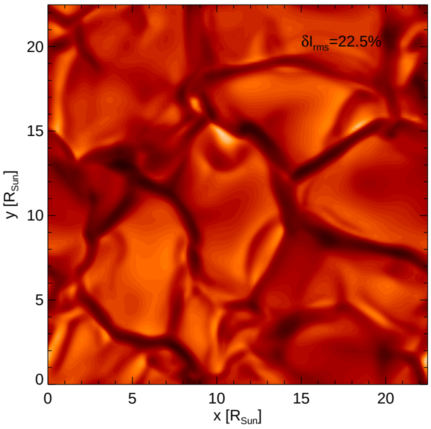

Figure 2. Snapshot of the emergent white light intensity during the temporal evolution of convective flows on the surface of a red giant ($T_{\rm eff}$ = 3700 K, $\log g$ = 1.0, $[M/H] = 0$). A typical granular pattern is discernible.

troscopic or photometric stellar properties. In contrast (see Figure 2), our hydrodynamical model predicts that convection affects the atmospheric layers, and a typical granulation pattern is present. As it turns out it is the result of intense convective overshooting.

The 1-D model atmosphere used in this comparison employed the same physical input data (opacities, equation of state, description of radiative transfer) as the hydrodynamical model. The convective energy transport was treated with mixing-length theory, turbulent pressure was neglected. Both aspects are of minor importance here since neither process influences the atmospheric structure of the 1-D model. For the 3-D model, direct calculation of broad-band colours is computationally too demanding, because of the complex geometry and time-dependence of the convective flow, and a large number of wavelength points necessary for a realistic description of the stellar spectrum. We instead approximated the hydrodynamical flow structure by classifying horizontal locations according to their white light emergent intensity, by sorting darker and increasingly brighter areas into nine intensity groups. For each group we calculated the average (in space and time) vertical thermal structure. The resulting nine thermal structures were treated as standard plane-parallel model atmospheres (the so-called 1.5-D approximation) in the subsequent spectral synthesis calculations. The resulting radiation fields were added according to the surface area occupied by their intensity group. Figure 3 shows the magnitude differences between broad-band fluxes of the 3-D and 1-D model. We find colour biases corresponding to temperature offsets of up to $\Delta T_{\rm eff} \sim 70$ K. This is a preliminary result obtained for a particular case but it illustrates limitations in the accuracy which we can in principle expect when interpreting observations in the framework of hydrostatic 1-D models. By the time Gaia is flying we expect that hydrodynamical model atmospheres are generally available for overcoming such limitations.

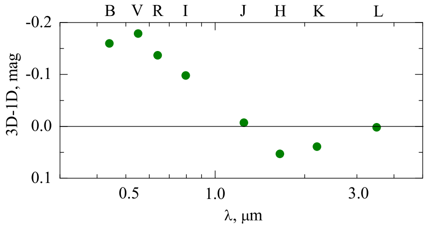

Figure 3. Influence of surface granulation on the broad-band photometric colours of a red-giant, as reflected by differences between the predictions of 3-D full hydrodynamical and classical 1-D model atmospheres. Note that differences in colour indices – in this representation directly given by the magnitude differences of the two selected bands – are significant, e.g., $\Delta(V-K) \sim$ 0.2 would correspond to $\Delta T_{\rm eff} \sim$ 70 K.

3-D hydrodynamical model atmospheres will also allow us to account for a number of qualitatively new effects. We find, for instance, that surface granulation due to convective overshoot in the upper photospheric layers will induce a luminosity variability on a peak-to-peak level of ~ 0.01 mag, on a time scales of one week. Additionally, intensity fluctuations on the stellar surface will also cause a stochastic movement of the stellar photocentre on the same time scale (Svensson & Ludwig 2005). Almost certainly, such phenomena will be routinely studied in 10–15 years from now, thus providing new windows for looking inside stars.

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