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THE GAIA RED CLUMP AS STANDARD CANDLE

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Abstract. Gaia has already provided new high precision parallaxes for two million objects, allowing to recalibrate standard candles. Red Clump stars are known to be good standard candles because of their small dependency of their luminosity on their stellar composition, colour and age. We developed methods to derive some of the main physical parameters to characterise the Red Clump as standard candle.

We provide fully empirical calibrations by using visual to infrared photometry, the most up-to-date 3D extinction map, and spectroscopic atmosphere parameters. We derived new calibrations for 16 Colour-$(G - K_{\mathrm{s}})$ and Effective Temperature-$(G - K_{\mathrm{s}})$ relations and a new calibration of the RC absolute magnitude on the Gaia G and 2MASS K_{s} bands. These calibrations are used afterwards to estimate the G-band interstellar extinction coefficient k_{G}. By combining of all these relations we implemented a method to determine effective temperatures and interstellar extinctions (A_0), which we will use in particular to derive asteroseismic parameters which can be directly compared with Gaia's results.

Keywords: stars: fundamental parameters, stars: abundances, stars: atmospheres, ISM: dust, extinction

1 Introduction

Standard candles play a fundamental role as a tool for distance determinations in astronomy. With the First Gaia Data Release (DR1) we have now access to new high precision parallaxes for two millions objects, with thousands of standard candles among them. In particular Red Clump (RC) stars are of special interest because we find a large number of them in the solar neighbourhood, allowing us to better characterise and parametrise them and therefore to improve distance estimations.

In this conference we briefly summarised the work detailed in Ruiz-Dern et al. (2017), Danielski et al. (in prep.) and Ruiz-Dern et al. (in prep.). In these papers we developed some methods to calibrate the RC photometrically in terms of colours, effective temperatures and absolute magnitudes, by using the Gaia G band. These calibrations were consequently used to derive the interstellar extinction coefficient in the G band (k_G). The whole set of fits is being applied to derive the effective temperatures of asteroseismic giants.

This paper first outlines the implemented methods to calibrate the colours, the effective temperatures, the absolute magnitudes and the extinction coefficient of RC stars, then focuses on the importance of high precision data to better describe the RC region, followed by the impact of our calibrations on the determination of asteroseismic distances and on the Gaia Validation process.

2 Empirical calibrations

In order to perform the calibrations, we first need to carefully select the sample. We considered several constraints to guarantee the quality of the data, and thus the quality of the final fits. The detail of the samples for each calibration may be found in Ruiz-Dern et al. (2017) for the colours, the effective temperatures and the absolute magnitudes, and in Danielski et al. (in prep.) for the k_G extinction coefficient. Nonetheless, some of the constraints are shared: the high photometric quality, the use of spectroscopic metallicities, the selection of just single stellar systems, and the cut on interstellar extinction using the most up-to-date 3D local extinction map of Capitanio et al. (2017) and the 2D map of Schlegel et al. (1998) when outside the cube. We kept only stars with $A_0 < 0.03$, where A_0 is the interstellar extinction at $\lambda = 550$ nm (Gaia reference value).

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2.1 Colours

In addition to the general constraints, for the colour-colour (CC) calibrations we selected red giant stars following two criteria: on the colour $G - K_\mathrm{s}$ and on the parallax ϖ, to avoid contamination from other spectral types:

$$G - K_s > 1.6 \tag{2.1}$$

$$m_G + 5 + 5\ \log_{10}\left(\frac{\varpi + 2.32\ \sigma_\varpi}{1000}\right) < 4 \tag{2.2}$$

where the factor 2.32 on the parallax error σ_ϖ corresponds to the 99th percentile of the parallax probability density function.

The general fitting formula adopted was:

$$Y = a_0 + a_1\ (G - K_\mathrm{s}) + a_2\ (G - K_\mathrm{s})^2 + a_3\ [\mathrm{Fe/H}] + a_4\ [\mathrm{Fe/H}]^2 + a_5\ (G - K_\mathrm{s})\ [\mathrm{Fe/H}] \tag{2.3}$$

where Y is a given colour, and a_i are the coefficients to be estimated. The photometric bands used for Y were: Gaia G, Hipparcos $B\ V\ H_\mathrm{p}$, Tycho $B_\mathrm{T}\ V_\mathrm{T}$, 2MASS $J\ K_\mathrm{s}$, and APASS $g\ r\ i$. A Monte Carlo Markov Chain (MCMC) method was implemented to fit this formula for each colour vs $G - K_\mathrm{s}$ relation in a robust way, by accounting for all variables uncertainties. Moreover, the process penalises the complex terms by using the Deviance Information Criterion (DIC) (Plummer 2008) and it checks outliers at 3σ from the fit, one by one.

2.2 Effective Temperatures

For the T_eff vs $G - K_\mathrm{s}$ calibration we applied the same criteria as for the CC calibrations sample. We then cross-matched the sample itself with the 13th release (DR13) of the APOGEE survey (SDSS Collaboration et al. 2016) in order to have a sample with homogeneous spectroscopic effective temperatures. When no Gaia parallax information was available (i.e. APOGEE stars not present in TGAS but in DR1) we kept stars with $\log g < 3.2$, using therefore only the Schlegel et al. (1998) map to apply our low extinction criteria. For the duplicated sources a weighted mean of the parameters was computed. To fit the sample we used the same method as in Section 2.1, with Y in Equation 2.3 the normalised effective temperature $\hat{T} = T_\mathrm{eff}/5040$ instead.

2.3 Absolute Magnitudes

Besides the general constraints, to calibrate the absolute magnitudes we selected stars within $1.93 < G - K_\mathrm{s} < 2.3$ and for which M_{K_s} is brighter than -0.5, to avoid contamination by the Secondary Red Clump. We did not consider any selection on the parallax relative precision, and the photometric uncertainties were neglected.

The adopted formula was:

$$M_\lambda = \alpha + \beta\ (G - K_\mathrm{s} - 2.1) \tag{2.4}$$

where the constant 2.1, the median of $G - K_\mathrm{s}$ of the sample, allows to center the fit on the RC.

The absolute magnitude is usually estimated through a Gaussian fit. However, one must consider the strong contamination of the RC by the Red Giant Branch Bump, as well as the variation of both populations with colour. Since here we are not modelling none of these populations we instead derived the absolute magnitude through the mode of its Gaussian distribution (Ruiz-Dern et al. 2017), which is less sensitive to the sample selection function. The colour dependency was therefore modelled by looking for the maximum of $Q(\alpha, \beta)$, a kernel based distribution function of the residuals $M_\lambda - (\alpha(G - K_\mathrm{s}) + \beta)$, with M_λ the absolute magnitude of each particular band. We derived M_λ for the Gaia G, Hipparcos $B\ V$, Tycho $B_\mathrm{T}\ V_\mathrm{T}$, 2MASS $J\ K_\mathrm{s}$, and APASS $g\ r\ i$ photometric bands.

2.4 k_G Extinction Coefficient

The stars selected for this calibration follow the same colour and parallax criteria as for the CC and T_eff calibrations (Sections 2.1 and 2.2), and have effective temperature, surface gravity and metallicity information from the APOGEE DR13 and the LAMOST DR2 surveys. Since the k_G calibration uses the T_eff fit derived in Section 2.2, only stars with $3603K < T_\mathrm{eff} \pm \sigma_{T_\mathrm{eff}} < 5207K$ and $-1.5 < [\mathrm{Fe/H}] < 0.4$ were used in order to work within the T_eff and [Fe/H] ranges of applicability of that relation (see Table 2 of Ruiz-Dern et al. 2017).

The adopted formula was:

$$k_\mathrm{G} = a_1 + a_2\ X + a_3\ X^2 + a_4\ X^3 + a_5\ A_0 + a_6\ {A_0}^2 \tag{2.5}$$

with X the intrinsic colour $(G-K_{\rm s})_0$ or the normalised effective temperature $\hat{T} = T_{\rm eff}/5040$, and a_i the coefficients to be estimated.

To derive the $k_{\rm G}$ extinction coefficient, first the colour excesses $\mathrm{E}(G-K_{\rm s})$ and $\mathrm{E}(J-K_{\rm s})$ were determined through the CC calibrations of Ruiz-Dern et al. (2017) (Section 2.1). Then the theoretical k_J and k_K were computed using the Fitzpatrick & Massa (2007) extinction law and the Kurucz Spectral Energy Distributions from Castelli & Kurucz (2003). All these informations were finally introduced into a Monte Carlo Markov Chain method (similar to the CC process) developed to accurately fit the empirical relation of Equation 2.5. The significance of the coefficients a_i was also tested through the Deviance Information Criterion.

3 Gaia vs Asteroseismology

The precision that is being achieved with Gaia will allow us from release to release to significantly improve the HR diagram. Consequently the different observational features that can be found on this diagram, such as the main and secondary RCs or even the Red Giant Branch Bump, will be more clearly detected.

Indeed, already with Gaia DR1 these different populations can be better observationally differentiated (Ruiz-Dern et al. 2017). In order to check the level of detail that we can achieve with Gaia DR1, in this work we compared this data to the asteroseismic Kepler/CoRoT database. To do so in a proper way, for Gaia we used a selection of stars with the quality criteria on photometry, spectroscopy and extinction mentioned in Section 2, and applied the bolometric corrections based on the ATLAS models and our $T_{\rm eff}$ calibration. For the asteroseismology data we used the Stellar Seismic Indices (SSI, LESIA - Observatoire de Paris)[*] for Kepler and CoRoT, together with the spectroscopic $T_{\rm eff}$ of the APOGEE DR13 and the LAMOST DR2 surveys.

We observed that our compilation allows to have a better defined asteroseismic HR diagram with an overall agreement on the shape with the Gaia DR1 HR diagram. Gaia DR2 should allow a much detailed study of each feature on the diagram and their variations with stellar populations.

3.1 New asteroseismic distances

By combining all the photometric calibrations mentioned in Section 2 in a proper way together with asteroseismic constraints, we can derive effective temperatures, interstellar extinctions and distance modulus for all the SSI stars. Indeed, we implemented a Monte Carlo Markov Chain method in magnitude space (Ruiz-Dern et al. in prep.) and used as input ingredients the asteroseismic parameters of all the SSI database (Kepler and CoRoT), our colour-colour and $T_{\rm eff}$ vs $G-K_{\rm s}$ photometric calibrations, and the $k_{\rm G}$ empirical relation. The method is independent of any metallicity or effective temperature input, although if available this information is used. We obtained homogeneous distance modulus for ~ 12000 stars of the SSI database.

3.2 Asteroseismology in the context of Gaia Data Validation

One of the main points to verify the accuracy of Gaia parallaxes is to check their zero-point and their precision. A way to do this is to select stars distant enough so that their estimated distance uncertainty is better than the Gaia parallax precision. Stars detected through asteroseismology fit in fact this description for Gaia DR1.

With this purpose, within the Gaia DR1 validation process we implemented a Maximum Likelihood Estimator method (Arenou et al. 2017) to estimate the offset z and the extra-variance q that should be taken into account in order for the Gaia parallaxes to be consistent with these external estimates:

$$P(z,q|t,\sigma_t,\varpi_G,\sigma_{\varpi_G}) \propto \int_{\varpi} \mathcal{N}\left[t, -5\ln\bar{\varpi}-5, \sigma_t\right]\, \mathcal{N}\left[\varpi_G+z, \bar{\varpi}, \sqrt{\sigma^2{}_{\varpi_G}+q}\right]\, d\bar{\varpi} \tag{3.1}$$

where t and σ_t are the external distance modulus and its uncertainty, ϖ_G and σ_{ϖ_G} the Gaia parallax and its uncertainty, and $\bar{\varpi}$ is the range of possible parallaxes within 5σ confidence interval:

$$\bar{\varpi} \in \left[\mathrm{Max}\left[\varpi-5\sigma, 0\right], \varpi+5\sigma\right]$$

For DR1 we used 1987 stars of the APOKASC (Apogee + Kepler) catalogue, which already provides distance modulus calculated by Rodrigues et al. (2014) using Padova isochrones relations. This gave us 984 Tycho sources with precision better than 0.1 mas (APOKASC median $\sigma < 0.02$). As described in Arenou et al. (2017) we

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[*] Stellar Seismic Indices: `http://ssi.lesia.obspm.fr/`

obtained a global bias zero-point of -0.060 ± 0.006 for the APOGEE stars, in agreement with other validation indicators (e.g. QSOs) detailed in the same article (see their Table 2). Our method, which takes into account the non-normal distribution of parallax errors in the distance modulus space, allows to find a much smaller offset than the one found in other studies (e.g. ~ 0.3 mas in De Ridder et al. 2016).

In parallel, the same test allowed to highlight a variation of parallax with magnitude. This could come, for instance, from a feature of stellar evolution models or from bolometric corrections. Both APOKASC and APOGEE showed a correlation between magnitude and colour, but while for APOKASC the brighter stars appeared bluer than the fainter ones (due to extinction effects on RC populations), for the APOGEE stars it was the opposite. In both cases though, the colour did not allow to explain the systematics seen in magnitude.

For Gaia DR2 we will be able to use the new homogeneous asteroseismic distances derived for the SSI database (Section 3.1) as input for this parallax zero-point verification.

4 Conclusions

We used Gaia Data Release 1 to derive fully empirical calibrations for colours, effective temperatures, absolute magnitudes and the extinction coefficient k_{G}, by using the Gaia G band, the most up-to-date 3D extinction map of Capitanio et al. (2017) and spectroscopic information. We took care of selecting high quality data and implemented robust methods for each parameter to guarantee the accuracy of the results. The extended and detailed work of all these calibrations may be found in Ruiz-Dern et al. (2017) and Danielski et al. (in prep.).

As stated, to select the samples of our calibrations we took advantage of the 3D extinction map of Capitanio et al. (2017). Then, the empirical fits obtained were combined to derive different physical stellar parameters, such as effective temperatures and interstellar extinctions. In particular, they have been used to determine the photometric interstellar extinctions for all the APOGEE stars. This has allowed us to provide a new important input to the 3D extinction map of Capitanio et al. (2017), and thus improving the current precision of the map.

Moreover, while Gaia DR1 was the main ingredient to obtain those calibrations, these have turned to be an ingredient for the verification of Gaia DR2 parallaxes. Indeed, the combination of these relations together with asteroseismic constraints allow us to derive homogeneous distance modulus for an important number of stars (Ruiz-Dern et al. in prep.). They will be used to check the Gaia parallax zero-point and extra-variance of DR2.

So far asteroseismology allows to provide a more detailed HR diagram. However, the combination of Gaia and asteroseismology data, and specially the forthcoming Gaia releases, will allow a deeper study of the different HR observational features, such as the main and secondary RCs or the Red and Asymptotic Giant Branch Bumps.

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