On the nature of black body stars

Aldo Serenelli\textsuperscript{1,2}, René D. Rohrmann\textsuperscript{3}, and Masataka Fukugita\textsuperscript{4,5}

\textsuperscript{1} Institute of Space Sciences (ICE, CSIC) Campus UAB, Carrer de Can Magrans, s/n, E-08193, Bellaterra, Spain
e-mail: aldos@ice.csic.es
\textsuperscript{2} Institut d’Estudis Espacials de Catalunya (IEEC), C/Gran Capita, 2-4, E-08034, Barcelona, Spain
\textsuperscript{3} Instituto de Ciencias Astronómicas, de la Tierra y del Espacio (CONICET), Av. España 1512 (sur), 5400 San Juan, Argentina
\textsuperscript{4} Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 277-8583 Japan
\textsuperscript{5} Institute for Advanced Study, Princeton, 08540 NJ, USA

February 12, 2019

ABSTRACT

A selection of 17 stars in the Sloan Digital Sky Survey, previously identified as DC class white dwarfs (WDs), has been reported to show spectra very close to blackbody radiation in the wavelength range from ultraviolet to infrared. Due to the absence of lines and other details in their spectra, the surface gravity of these objects has not been previously well constrained and their effective temperatures have been determined by fits to the continuum spectrum using pure helium atmosphere models. We compute model atmospheres with pure helium and H/He mixtures and use Gaia DR2 parallaxes available for 16 out of the 17 selected stars to analyze their physical properties. We find that the atmospheres of the selected stars are very probably contaminated with a trace amount of hydrogen as \( -6 \leq \log (N_{\text{H}}/N_{\text{He}}) \leq -5.4 \). For the 16 stars with Gaia parallaxes, we calculate a mean stellar mass \( 0.606 \pm 0.076 M_\odot \), which represents typical mass values and surface gravities (7.8 < \( \log g < 8.3 \)) for WDs.

Key words. white dwarfs — stars: atmospheres — stars: evolution — opacity

1. Introduction

DC type white dwarfs (WDs) comprise degenerate stars showing only continuous spectra which are commonly attributed to helium-rich atmospheres with effective temperature \( T_{\text{eff}} \) lower than \( \approx 11000 \) K. Specifically, they have long been recognized as descendants of DB class stars (WDs with He I lines and no other elements present in their spectra) as they cool down below the spectral line detection (Baglin & Vauclair\textsuperscript{1973}). It was also suggested by Baglin & Vauclair that some DC WDs could be a result of the mixing in convective DA stars (almost pure H atmospheres). This process was proposed to explain the so-called non-DA gap in the range 5000 K \( \leq T_{\text{eff}} \leq 6000 \) K where few non-DA stars are found (Bergeron et al.\textsuperscript{1997}). Using evolutive models and statistical analysis, Chen & Hansen\textsuperscript{2012} showed that such a deficit could originate from a combination of convective mixing and a higher cooling rate of the post-mixing WDs. In addition, recent studies have shown a bifurcation of helium- and hydrogen-atmosphere cooling sequences on color-magnitude diagrams of Sloan Digital Sky Survey (SDSS) and Gaia passbands (Gaia Collaboration et al.\textsuperscript{2018a}, Kilic et al.\textsuperscript{2018}) with both sequences coinciding below \( T_{\text{eff}} \approx 7000 \) K, where a high number of DC stars are confined. The observed split in the two sequences could be not only due to atmospheric composition, but also to an effect of the stellar mass distribution (Kilic et al.\textsuperscript{2018}). Clearly, further work is necessary to understand the role of DC stars in the chemical evolution of cool WD atmospheres.

Recently, Suzuki & Fukugita (2018, hereafter SF18) have identified a group of stars that exhibit almost perfect blackbody spectra with no apparent absorption lines, which SF18 referred to as blackbody stars and to which we refer here simply as the SF18 sample or SF18 stars. Their study included mainly spectrophotometric data of the SDSS in DR7, but was also supplemented with ultraviolet photometry of Galaxy Evolution Explorer (GALEX) and infrared data of the Wide-field Infrared Survey Explorer (WISE). The selected group of objects, composed by 17 stars that mimic the blackbody emission, were previously classified as DC WDs in a number of studies based on spectral, photometric and kinematics analyses (Kleinman et al.\textsuperscript{2004}, Eisenstein et al.\textsuperscript{2006}, Kleinman et al.\textsuperscript{2013}, Kepler et al.\textsuperscript{2015}, Gentile Fusillo et al.\textsuperscript{2015}). The potential interest of this sample relies on the simplicity of their spectral energy distributions, which makes them excellent objects for calibration purposes of photometric (SF18) and spectroscopic surveys (Lan et al.\textsuperscript{2018}, Narayan et al.\textsuperscript{2018}). Deviations of the SF18 stars from blackbody colors from infrared to UV are really minute. The lack of spectral features prevents an accurate evaluation of the surface gravity (\( g \)), and previous effective temperature evaluations have been based on photometric and continuum spectrum fits with pure helium models. However, it is particularly unclear whether the continuum spectrum of pure-He atmosphere white dwarfs can lead to a spectral energy distribution that mimic so well that of a black body spectrum in the whole temperature range covered by the SF18 sample. A study of these stars, also, could provide further insight about the chemical evolution of cool WDs. Furthermore, this subpopulation of DC stars could also open a novel possibility of testing our understanding of cool, high-density stellar atmospheres.

In this work we study the stellar parameters of the SF18 sample by considering the spectral properties of white dwarf model atmospheres computed with different assumptions regarding their composition. We find that pure-He atmosphere models produce a blackbody spectrum that matches the observed sample of DC stars, but require high surface gravities for the cooler stars. Atmospheres dominated by helium that contain a trace amount
of hydrogen can also reproduce the data very well, with log $g$ values more typical for WDs. The effective temperature of the models that fit best these stars differs, however, from the estimated blackbody temperature ($T_{BB}$) due to opacity effects. The difference between these temperatures depends on the blackbody temperature as well as on the amount of hydrogen pollution of the atmosphere. The inclusion of the Gaia data allows us to determine the physical parameters of these stars, their temperature, radius, mass and surface gravity, with the aid of atmosphere models, to a good precision, removing the ambiguity present when only photometry is available. We find the mass distribution of this sub-group of DC stars to be similar to that of (hotter) DB stars. This leads us to provide support that this sample of DC stars are cooler descendants of DBs.

The layout of the paper is as follows. In Section 2 we briefly review the model atmospheres used in this work. In Section 3 we show that models with pure-He composition or very low hydrogen pollution reproduce the blackbody properties of the SF18 stars, and in Section 4 we determine the stellar parameters of the stars. In Section 5 we discuss our results in the context of the evolution of DB and DC stars, as well as the potential use of the SF18 sample as calibrators for both photometric and spectroscopic surveys. Finally a summary and conclusions are presented in Section 6.

2. WD atmosphere models

The white dwarf model atmospheres used in this work have been computed within the assumption of plane-parallel geometry, LTE, radiative-convective and hydrostatic equilibrium. Convective energy transport is treated in the mixing-length approximation (ML2, e.g. Salaris & Cassisi 2008). Particle populations for LTE, radiative-convective and hydrostatic equilibrium. Convection is treated with the ML2 scheme of Salaris & Cassisi (2008). Particle populations for a mixture of hydrogen and helium ($H$, $H_2$, $H^+$, $H^-$, $H_2^+$, He, He$^+$, He$^{-}$, He$^0$, He$^+$, He$^{++}$, HeH+, and e$^−$) are derived from the occupation probability formalism. All relevant radiative opacities are considered. Details of the code can be found in Rohrmann et al. (2012) and references therein. We use two classes of models according to composition: pure-He, and He-dominated atmospheres with H abundances log ($N_H/N_{He}$) = −2,...,−8.5. Results for pure hydrogen atmospheres are also considered but only for reference.

3. SF18 stars in the color-color plane

We present in Figure 1 the ($u−g$) vs ($g−r$) color-color diagram for white dwarfs from the SDSS DR7 white dwarf catalog (Kleinman et al. 2013), where $u$, $g$, $r$ are the SDSS color bands (Fukugita et al. 1996). We include DB (He I 4471 Å) and DC (featureless spectrum) with the spectroscopic classification taken from the original catalog. Randomly selected samples are shown for each class to avoid overcrowding the plot. The 17 stars of the SF18 sample are shown as black data points with error bars.

Figure 1 includes theoretical predictions for different classes of white dwarf atmosphere models characterized by their composition. The orange solid line represents the predictions of pure-He atmosphere models for varying $T_{eff}$ from about 14000 K (upper left mark) down to 7000 K (lower right mark) with a 1000 K step. Pure-He atmospheres have colors very different from a blackbody spectrum in the temperature range of interest. These models are shown with blue long-dashed lines in Fig.1 Colors of atmospheres composed of H/He mixtures vary with the relative abundance of H with respect to He. The dotted lines in the figure denote sequences of models with constant $T_{eff}$ and decreasing amount of hydrogen going from pure-H to pure-He model atmospheres. Here, yellow circle ticks denote log ($N_H/N_{He}$) = −2,...,-4, and -6. When the H/He ratio decreases to log ($N_H/N_{He}$) ≲ −6, they approach close to the pure-He models, within the photometric uncertainties of the SF18 sample. It is to be noted that for log ($N_H/N_{He}$) ≲ −6 hydrogen lines remain hidden in helium-rich atmospheres; the equivalent width of Hα drops below ~ 0.2 Å (Weidemann & Koester 1995). All models in the figure correspond to log $g$ = 8: ($u−g$) and ($g−r$) colors from pure-He atmospheres depend very weakly on log $g$. Finally, the green short-dashed line represents results for blackbody spectra. Circle ticks represent temperature intervals of 1000 K.

Note that the SF18 sample falls exactly on top of the blackbody predictions. This is the result of the selection of stars done by SF18, in which a star with a spectrum that deviated substantially from a blackbody, was discarded. All stars in the sample have a blackbody temperature $T_{BB}$ between 7000 K and 12,000 K, defined as the temperature of a blackbody that reproduces all observed colors. In this temperature range, colors from pure-He models almost perfectly overlap with blackbody colors. This is also true for models with log ($N_H/N_{He}$) = −6. At hotter ($g−r < −0.15$) temperatures pure-He model predictions start to deviate from the blackbody results. The same is true for the cooler temperatures ($g−r > 0.25$), as shown below in Fig. 2. These results support the identification of stars in the sample as DC stars either with pure-He envelopes or with very small amount of H. On the other hand, it is evident from the figure that DC stars do not always display colors that match those of a blackbody and, in this regard, the SF18 sample represents a
peculiar minority of the whole DC population. Note that DC is a label of observational classification that implies the absence of spectral features. While this is usually understood as due to He-dominated atmospheres, it includes stars with trace abundances of other chemical elements with abundances low enough to not show spectral lines but large enough to affect the shape of the continuum.

It is possible that the SF18 sample is formed by DQ stars with very small traces of carbon, too low to have any discernible feature in SDSS spectra. Koester & Knist (2006) have shown that in C/He atmospheres the effect of carbon in the $(u - g)$ vs $(g - r)$ plane vanishes for $N_c/N_{He} < -8$ in the temperature range of the SF18 stars. Spectroscopically, the lowest carbon abundance measured in DQ stars is $N_c/N_{He} \approx -7.5$ (Koester & Knist 2006, Kepler et al. 2015). On the other hand, evolutionary models (Camasassa et al. 2017) indicate that stars with initially pure-He envelopes undergo a rapid enrichment of carbon due to dredge up as stars cool down from $T_{eff} \approx 12500$ K to 7000 K. The carbon abundance then increases up to log ($N_c/N_{He}$) $\approx -3$ for white dwarf models of different stellar mass. However, in order for the SF18 stars to have a C abundance below the detectability level but large enough to affect colors, a finely tuned competition between dredge up and gravitational sedimentation has to occur throughout this effective temperature range. This possibility is made even less probable by the fact that the sample includes stars of similar mass and effective temperatures that differ by a few thousand degrees, a range over which models show much larger variations in surface C abundances than allowed by detectability limits.

The comparison between models and data is more revealing when UV bands are included. Figure 2 compares the SF18 sample with our models in the Galex (FUV-NUV) vs $(g - r)$ plane. All stars are perfectly matched to the blackbody color due to their selection criterion in SF18, which included UV photometry. Pure-He models also provide a good description of the data for stars bluer than $(g - r) > 0.1$. For cooler stars with $(g - r) > 0.1$, however, the log $g = 8$ canonical pure-He model deviates from the blackbody results, and does not reproduce, in particular, the three coolest stars. UV colors from pure-He models show a larger sensitivity to log $g$ than optical colors, and models with log $g = 9$ remain close to blackbody colors at cooler temperatures. This would suggest that the cool stars could be quite massive white dwarfs with masses around 1.2 $M_\odot$, i.e. in the realm of WDs with ONe or CO-Ne hybrid cores rather than typical CO cores (Althaus et al. 2005, Doherty et al. 2017). A more satisfactory result is found with the He/He models with log ($N_{He}/N_{He}$) = -5.4, -6 also shown in Figure 2. These models at log $g = 8$ reproduce colors of the SF18 sample better than pure-He models across the whole range, corresponding to typical WD masses of about 0.6 $M_\odot$ in agreement with the mean mass value for DBs (e.g. Koester & Kepl 2015). We come back to this in the next section, in which we determine stellar parameters using the recent astrometric results of Gaia DR2 (Gaia Collaboration et al. 2018b).

4. Determination of physical parameters

The physical parameters of the stars, in particular radius and mass, can be determined with the aid of model atmospheres, provided their distances are known. The recent Gaia DR2 (Gaia Collaboration et al. 2018b) includes astrometric solutions for 16 out of the 17 SF18 stars. We have queried the Gaia DR2 catalog using CosmoHub (Carretero et al. 2017). Parallaxes range between 4.5 and 14 mas, i.e. distances between 70 and 230 pc, and errors between 1% and 10% with a mean of 4.5%, not far from end-of-mission expectations. Parallaxes and distances are listed in Table [1].

In order to determine the stellar radius, we consider the relation, valid for SDSS magnitudes:

$$m_b = -2.5 \log \left[ \pi R^2 \sigma \right] - 2.5 \log \left[ \frac{F_\nu S_{\nu,dd} d\nu}{S_{\nu,dd}} \right] - 48.60,$$

where $m_b$ is the observed magnitude in a given band $b$, $\sigma$ is the parallax, $R$ the radius, $F_\nu$ the astrophysical flux, and $S_{\nu,dd}$ the passband transmission in band $b$. From the observed colors, $T_{BB}$ can be derived straightforwardly. But in the relation above, $F_\nu$ depends on the unknown $T_{eff}$. Therefore, model atmospheres are required to relate the observationally determined $T_{BB}$ with $T_{eff}$ which, in turn, is used to determine $F_\nu$.

The relation between $T_{BB}$ and $T_{eff}$ depends on the physical conditions of the stellar atmosphere. To illustrate this, we compare in Figure 3 the emerging flux of a $T_{eff} = 10000$ K (log $g = 8$) pure-He atmosphere with a blackbody spectrum also at $T_{eff} = 10000$ K, i.e. both models have the same flux $f(T_{eff}) = \sigma T_{eff}^4$, where $\sigma$ is the Stefan-Boltzmann constant. The spectrum of the pure-He model is slightly shifted towards the bluer side, compared to the black body spectrum of the same $T_{eff}$. The figure also shows the spectrum of a pure-He model at $T_{eff} = 9379$ K, which mimics the shape of a $T_{eff} = 10000$ K blackbody spectrum and hence its colors, but differ in the flux normalization, which is smaller by a factor (3973/10000)$^4 = 0.774$.

The blueward shift of the spectrum of pure-He models with respect to a blackbody of the same $T_{eff}$ can be understood by looking at Figure 4 which shows the different contributions to the opacity of the model with $T_{eff} = 9379$ K at optical depth $\tau_{Ross} = 1$. Opacity is dominated by He$^{-}$ free-free (ff) processes and by bound-free (bf) processes of He$^{+}$ as the secondary agent.
These opacity sources have a relatively weak dependence with frequency across most of the spectrum up to the dominant ff He\(^+\) contribution that increases towards longer wavelengths (see Fig. 3). Increased flux blocking at longer wavelengths shifts the spectrum towards the blue, giving it the shape of a blackbody of higher temperature at the same integrated flux. In the model shown in Fig. 3, ff transitions in He\(^+\) become the single most important opacity source for frequencies larger than 5 \(\mu\)m\(^{-1}\), and increase for higher frequencies. Therefore, it is expected that colors involving UV bands will show deviations from blackbody processes of higher temperature at the same integrated flux. In the model shown in Fig. 3, increased flux blocking at longer wavelengths shifts the spectrum towards higher frequencies making it appear hotter, i.e. \(T_\text{BB} > T_\text{eff}\).

We note that the temperature for the SF18 stars may be somewhat lower, by 100\(E(B-V)/0.01\) K, when extinction to these local white dwarfs is taken into account (SF18), while \(E(B-V)\) is typically 0.02 mag/(100pc) in the solar neighbourhood. It is difficult to determine extinction for individual WDs from photometry, since extinction is nearly parallel to the change of temperature. Extinction hardly affects the extent of the deviation of stars from these stars from the blackbody curve.

In order to determine \(R\) from Eq. [1], we have used three different sets of model atmospheres: 1) He-pure with \(g = 8\); 2) He-pure with \(g = 9\); 3) \(\log(N_{\text{He}}/N_{\text{He}}) = -6\) and \(g = 8\). For each case the difference \(T_\text{BB} - T_\text{eff}\) can be approximated analytically to better than 30 K as:

\[
\begin{align*}
T_\text{BB} - T_\text{eff} &= \frac{625 + 0.07x + 1.41 \times 10^{-5}x^2}{817 - 0.023x + 1.15^{-5}x^2}, \\
&\text{where } x = T_\text{BB} - 10000. \\
\end{align*}
\]

Fig. 3. Emerging monochromatic flux. Orange short dashed line: pure-He atmosphere with \(T_\text{eff} = 10000\) K; solid green line: blackbody spectrum with \(T_\text{eff} = 10000\) K; blue long dashed line: pure-He atmosphere with \(T_\text{eff} = 9379\) K; red dotted line: pure-He atmosphere with \(T_\text{eff} = 9379\) K scaled up by a factor 1.29 to match the total flux of a \(T_\text{eff} = 10000\) K spectrum. Model atmospheres correspond to \(\log g = 8\).
Fig. 5. Top three panels: absolute difference of colors between blackbody spectrum and pure-He atmospheres (red-dotted), log \((N_{\text{He}}/N_{\text{He}}) = -6\) models (solid blue), and best-fit model (dashed orange). Circles denote residuals for the SF18 stars. Fourth panel from top: log \((N_{\text{He}}/N_{\text{He}})\) values for the best-fit model (dashed orange) and log \((N_{\text{He}}/N_{\text{He}}) = -6\) (solid blue, constant). Lower panel: \(T_{\text{BB}} - T_{\text{eff}}\) as a function of blackbody temperature and hydrogen abundance for pure-He, log \((N_{\text{He}}/N_{\text{He}}) = -6\), and best-fit models.

Fig. 6. \(T_{\text{eff}}\) and radius of stars in the SF18 sample with measured Gaia parallaxes. Results for different sets of model atmospheres are shown as: red circles (log \(g = 8\), He-pure models), blue squares (log \(g = 9\), pure-He models), black dots with error bars (log \(g = 8\), log \((N_{\text{He}}/N_{\text{He}}) = -6\)). Overlaid with long-dashed lines are theoretical WD evolutionary tracks for 0.606 \(M_\odot\) (CO-core) and 1.16 \(M_\odot\) (ONe-core) WD models. Short dashed lines show curves of constant log \(g\) determined from evolutionary models.

(2017) and ONe-core models from [Althaus et al. 2005]. Error bars, shown for one case only, are determined using photometric uncertainties from SF18, Gaia DR2 parallax errors and \(T_{\text{eff}}\) errors from the uncertainties in fitting \((u-g), (g-r), (FUV-NUV)\) colors.

Results in Fig. 5 show that, regardless of the assumptions underlying the model atmospheres used, the radii of all the stars are consistent with them being CO white dwarfs, ruling out that they are massive WDs. Radii estimated with log \(g = 8\) models and log \((N_{\text{He}}/N_{\text{He}}) = -6\) are systematically larger than those obtained using He-pure models with the same log \(g\), and the difference increases towards lower temperatures. This reflects that, for given \(T_{\text{BB}}, T_{\text{eff}}\) is lower for log \((N_{\text{He}}/N_{\text{He}}) = -6\) models (bottom panel in Fig. 5).

Our results show that, by combining photometric and astrometric data, observational properties of stars in the SF18 sample are well described by log \(g = 8\) and log \((N_{\text{He}}/N_{\text{He}}) = -6\) WD model atmospheres. We therefore use stellar radii determined using these models as our reference values for the determination of further properties, log \(g\) and mass, of the SF18 stars. Our derivations make use of the DB evolutionary tracks from [Camisassa et al.] (2017). Final results are reported in Table 1.

5. Discussion

Figure 7 compares our \(T_{\text{eff}}\) and log \(g\) determinations, in blue with error bars, with previous results from the literature [Eisenstein et al. 2006; Kleinman et al. 2013; Kepler et al. 2015], based on photometry adopting He-pure model atmospheres without astrometric data. The large scatter in log \(g\) found in previous results stems from the difficulty in the determination for DC stars which lack spectral lines. It is only with the inclusion of Gaia parallaxes that this can be improved substantially. It should also be noted that using He-pure model atmospheres affects the determination of \(T_{\text{eff}}\), as shown in previous sections.

Very recently, [Gentile Fusillo et al. 2019] hereafter G19) presented a catalogue of white dwarfs with SDSS photometry and Gaia DR2 astrometry. They have determined stellar parameters using either H-pure or He-pure model atmospheres for all stars in the catalogue. Differences between our \(T_{\text{eff}}\) and log \(g\) determinations with those obtained with He-pure models by G19 are shown in Figure 8. The difference in \(T_{\text{eff}}\) determinations propagates to log \(g\) because a known distance fixes the stellar flux \(F_{\nu}\), so that changes in \(T_{\text{eff}}\) need to be compensated by changes in the inferred stellar radius. There are two likely reasons for the difference in the \(T_{\text{eff}}\) determinations. We have complemented the SDSS ugriz data with Galex UV photometry and used H/He model atmospheres, required to reproduce UV colors.

The mass distribution of our sample has a mean value of \(\langle M_{\text{SF18}} \rangle = 0.606 M_\odot\) and a dispersion \(\sigma_{M_{\text{SF18}}} = 0.075 M_\odot\). Results from G19, on the other hand, give \(\langle M_{\text{SF18}} \rangle = 0.651 M_\odot\) with \(\sigma = 0.059 M_\odot\). The difference can be explained because G19 used He-pure models. When we redo our analysis using He-pure model atmospheres we obtain \(\langle M_{\text{SF18}} \rangle = 0.649 M_\odot\). Neglecting the presence of small traces of H in the atmospheres can lead to overestimate of mass by about 10%, a systematic difference larger than the precision with which the stellar mass is determined.

We also compare the mass distribution of our sample with those of stars available in the literature. [Koester & Kepler 2015] has obtained \(\langle M_{\odot} \rangle = 0.606 M_\odot\) with 1-\(\sigma\) dispersion between 0.04 and 0.1 \(M_\odot\) depending on the \(T_{\text{eff}}\) range analyzed. More re-
natural text
We find that these stars are cool He-rich WDs polluted by hydrogen, in the range $-6 < \log \left( N_{\text{He}} / N_{\text{H}} \right) < -5.4$, having a typical WD mass. The hydrogen abundance has a lower limit imposed by the necessary contribution of free electrons so that blackbody colors are reproduced even for the coolest stars in the sample, an effect particularly important when considering UV colors. The upper limit is given by the absence of apparent spectral features. The narrow range allowed by these two conditions is a possible reason for the paucity of stars with nearly perfect blackbody colors, such as those in the SF18 sample, among the much larger set of DC WDs.

The inclusion of Gaia parallaxes allows a refined determination of the surface gravity of the stars, otherwise badly constrained due to the lack of spectral lines. We have also shown that using He-pure models, as done recently in the literature, leads to systematic offsets in $T_{\text{eff}}$ determinations. Moreover, using He-pure models tends to overestimate the masses of these stars by about 10%. It is important to note that these systematic errors might be a common feature affecting the determination of stellar parameters of many, if not all, DC stars for which trace elements are not detected in their spectra but have an effect on their photometric properties. The mass distribution for the stars in the SF18 sample agrees very well with that of (hotter) DB stars, giving a strong support to the idea that DC stars are their cool descendants.

Finally, we reinforce the possibility, already realized and tested in SF18, that the simplicity of the spectral energy distributions of these stars offers very good potential for calibration of photometric and spectroscopic surveys at the sub-percent level, without the need to rely on stellar model atmospheres.

Acknowledgements. We thank the anonymous referee for the comments that have helped improving the article. We would like to thank Max-Planck-Institut für Astrophysik (MPA) where this work was initiated. AS is partially supported by the Spanish Government (ESP2017-82674-R) and Generalitat de Catalunya (2017-SGR-1131). RDR thanks the support of the MINCYT (Argentina) through Grant No. PICT 2016-1128. MF thanks Hans Bohringer and late Yasuo Tanaka for the hospitality at the Max-Planck-Institut für Extraterrestrische Physik and Eichiro Komatsu at MPA, in Garching. He also thanks Alexander von Humboldt Stiftung for support during his stay in Garching, and Monell Foundation in Princeton. He received in Tokyo a Grant-in-Aid (No. 15430000110) from the Ministry of Education. Kavli IPMU is supported by World Premier International Research Center Initiative of the Ministry of Education, Japan. This work has made use of CosmoHub developed by the Port d’informacio Científica (PCI), maintained through a collaboration of the Institut de Física d’Altes Energies (IFAE) and the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), and was partially funded by the “Plan Estatal de Investigación Científica y Técnica y de Innovación” program of the Spanish government.

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