Supersolar metallicity in G0–G3 main sequence stars with V<15

R. López-Valdivia, E. Bertone, M. Chávez, C. Tapia-Schiavon, J. B. Hernández-Águila, J. R. Valdés, and V. Chavushyan

1 Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro 1, Tonantzintla, Puebla, 72840, México
2 Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 372 (Xangari), 58090 Morelia, Michoacán, México

ABSTRACT
The basic stellar atmospheric parameters (effective temperature, surface gravity and global metallicity) were simultaneously determined for a sample of 233 stars, limited in magnitude (V<15) with spectral types between G0 and G3 and luminosity class V (main sequence). The analysis was based on spectroscopic observations collected at the Observatorio Astofísico Guillermo Haro and using a set of Lick-like indices defined in the spectral range of 3800–4800 Å. An extensive set of indices computed in a grid of theoretical spectra was used as a comparison tool in order to determine the photospheric parameters. The method was validated by matching the results from spectra of the asteroids Vesta and Ceres with the Sun parameters. The main results were: i) the photospheric parameters were determined for the first time for 213 objects in our sample; ii) a sample of 20 new super metal-rich stars candidates was found.

Key words: Stars: atmospheres, stars: fundamental parameters, stars: solar-type

1 INTRODUCTION
Stellar atmospheric parameters are of fundamental importance in a plethora of astrophysical scenarios. On the one hand, effective temperature and surface gravity (T_{\text{eff}} and \log g) and, to some extent, chemical composition allow, for instance, to properly locate stars in the HR diagram and therefore to better establish their evolutionary status and ages. This has been particularly true for segregating stars on the main sequence from evolved objects in the Kepler field in a wide temperature range (Molenda-Zakowicz et al. 2013). They are also important in identifying solar analogues or twins that permit to place our Sun into context of its neighbourhood (Porto de Mello et al. 2014).

On the other hand, the stellar chemical composition turns out to be a primary criterion in the analysis of the chemical history of galaxies, including our Milky Way. Global metallicity ([M/H]) provides, in the case of metal-poor stars, information on the early stages of galaxy evolution, before the rapid insertion of enriched yields through supernovae events shaped their observable chemical properties. Less attention, however, was initially paid to the super metal-rich (SMR) stars, in spite of having been defined more than four decades ago by Spinrad & Taylor (1969) as stars with metallicity higher than the Hyades. This leading (and controversial) study and that of Rich (1988) on the galactic bulge have for a long time served as the basis for investigations of metal-rich extragalactic populations, such as those found in elliptical galaxies and spheroidal components (mainly bulges) of spirals. In this work, we adopt a threshold of +0.16 dex for a star to be considered SMR; this value is slightly more conservative than the recent estimate of the average metallicity of the Hyades ([Fe/H]=0.13±0.06 dex), reported by Heiter et al. (2014).

More locally, SMR stars have become particularly interesting objects in view of the well established correlation between the presence of giant exoplanets and the stellar metal content (Gonzalez 1998; Santos et al. 2001; Fischer & Valenti 2005). Such correlation indicates that the probability of finding a giant planet significantly increases with increasing metallicity. It is now known that 25% of metal-rich nearby field stars harbor planets, while the prevalence is reduced to 3% if we consider solar abundances (Santos 2008). The metallicity-planet correlation has posed interesting challenges to the current planet formation scenarios, since it appears to favour the core accretion model (Alibert, Mordasini & Benz 2004) over the planetary formation as a result of disk instabilities (Boss 1997). It has also motivated a number of studies in search for giant exoplanets in field stars as well as in metal-rich stellar clusters as NGC 6791 (Bruntt et al. 2003).
To date, SMR stars are attractive on both of the above scenarios, and studies in one field have been shared by the other. For instance, the construction of stellar databases as tools for the synthesis of stellar population have recently been incorporated in exoplanetary studies (Buzzoni et al. 2001). Conversely, stellar studies, aimed at finding fiducial targets for exoplanet searches and potential correlations between stellar host properties and the presence of substellar companions, have already impacted broader issues, as the chemical evolution of the Milky Way (see Neves et al. 2008; Adibekyan et al. 2011, 2012; and references therein).

In this work, we carried out a spectroscopic analysis of a sample of stars of spectral types G0–G3, luminosity class V, in the visual magnitude interval 4.05 < V < 14.77, that has been observed at moderate resolution (FWHM 2.5 Å). We simultaneously derive the three leading atmospheric parameters (\(T_{\text{eff}}\), \(\log g\) and \([\text{M/H}]\)), through the study of their spectroscopic indices, and identify a new sample of SMR stars as potential targets of planet searches.

2 STELLAR SAMPLE AND OBSERVATIONS

We selected in late 2008 a sample of stars from SIMBAD database using the following criteria: i) spectral type between G0 and G3; ii) luminosity class V; iii) visible magnitude \(V < 15\) mag; and iv) declination \(\delta > -10^\circ\). The selection resulted in about 1200 objects. We report here the results for 233 stars. We carried out the spectroscopic observations at the 2.12 meter telescope of the Observatorio Astrofísico Guillermo Haro (Sonora, Mexico) between 2008 and 2013, with a Boller & Chivens spectrograph, equipped with a Versarray 1300x1340 CCD. The grating of 600 l/mm and the slit width of 200 μm provided a constant spectral resolution of 2.5 Å FWHM and a dispersion of 0.7 Å px\(^{-1}\) along the wavelength range between about 3800 and 4800 Å. Typically, we acquired 2 or more images for each star, with total exposure times between 3 min, for the brighter objects, and about 60 min for the fainter ones, to reach a signal-to-noise ratio per pixel (S/N) of 30–80, computed in a window of 100 Å around 4600 Å. The sample is presented in Table 1 where we list the star identification, the \(V\) magnitude and the spectral type as given in SIMBAD. In Fig. 1 we show the distribution of the \(V\) magnitude for the stars in our sample.

1 The S/N is the average value given by a moving standard deviation over a 5 Å-wide window. Since in the spectra part of the standard deviation is caused by real absorption lines, the S/N values, which therefore also depend on photometric parameters, should be considered as lower limits.

2 Since the first selection, back in 2008, six stars no longer would accomplish the spectral type criterion. Three objects (HD 19373, HD 100180, and BD+31 4162) are still classified as main sequence and their re-classification ascribes them a slightly hotter status of, at most, one spectral sub-class. The star HD 105898 appears originally classified as G2 V, in Table VII of Eggen (1964), but now the classification corresponds to a cooler and evolved object (G6 III–IV). HD 137510 appears classified as G2 V in [Harlan & Taylor (1970)]. and currently the SIMBAD type is G0 IV-V. Finally, the star HD 149996 now lacks luminosity class, although it has been designated as dwarf by Bonifacio et al. (2000).

| Name | \(V\) (mag) | Spectral type |
|------|-------------|--------------|
| HD 236373 | 10.22 | G0V |
| IRXS J003845.9+332534 | 10.33 | G2V |
| [BHGS8] 40 1943 | 14.77 | G2V |
| HD 4602 | 9.04 | G0V |
| BD+59 140 | 10.37 | G2V |
| TYC 4497-874-1 | 10.92 | G3V |
| HD 5649 | 8.70 | G0V |
| TYC 4017-1351-1 | 11.22 | G0V |
| BD+60 167 | 10.34 | G0V |
| BD+02 189 | 10.29 | G1V |

Figure 1. Distribution of \(V\) magnitude for all the sample.

In addition to the sample described above, we also observed a set of 29 reference stars from the PASTEL catalogue (Soubiran et al. 2010) and complemented this sample with 35 objects from Liu et al. (2008). The reference sample will serve to test the adequacy of theoretical spectra in a range of atmospheric parameters, as explained in Sect. 4.1. The main photospheric parameters (see Table 2) of these objects were obtained by averaging only those PASTEL entries that provide the three parameters \(\{T_{\text{eff}}, \log g, [\text{M/H}]\}\) to minimize the effect of degeneracies. The reference stars span 4857–6987 K in effective temperature, 3.00–4.68 dex in surface gravity and -1.43 – +0.30 dex in global metallicity.

Since we know with great accuracy the photospheric parameters of the Sun, we also observed, in February 2013, its spectrum reflected by the asteroids Vesta and Ceres, using the same observational set-up and a CCD600 camera which provides a slightly larger dispersion of 1.0 Å pixel\(^{-1}\). At the time of the observation, they had \(V=7.71\) and 8.05 mag, respectively. We took five exposures of each target, for a total of 780 and 750 seconds, respectively, providing S/N≈60.

The data were reduced following the standard procedure in IRAF: bias subtraction, flat field correction, cosmic ray removal, wavelength calibration (by means of an internal HeAr lamp), and flux calibration (using spectrophotometric standard stars from the ESO list. We then shifted all spectra to the rest frame, using an average radial velocity obtained from measuring the shift of several absorption lines along
Table 2. The atmospheric parameters for the 64 reference stars.

| Star      | $T_{\text{eff}}$ (K) | $\log g$ (dex) | $[\text{M/H}]$ (dex) | Star      | $T_{\text{eff}}$ (K) | $\log g$ (dex) | $[\text{M/H}]$ (dex) | Star      | $T_{\text{eff}}$ (K) | $\log g$ (dex) | $[\text{M/H}]$ (dex) |
|-----------|----------------------|----------------|-----------------------|-----------|----------------------|----------------|-----------------------|-----------|----------------------|----------------|-----------------------|
| HD3651    | 5205                 | 4.49           | 0.10                  | HD99285   | 6590                 | 3.84           | -0.22                 | HD134083  | 6537                 | 4.31           | 0.02                  |
| HD3765    | 5034                 | 4.53           | 0.05                  | HD100180  | 5927                 | 4.25           | -0.06                 | HD134113  | 5680                 | 4.06           | -0.78                 |
| HD15335   | 5858                 | 3.93           | -0.18                 | HD100563  | 6401                 | 4.03           | 0.05                  | HD136064  | 6121                 | 4.03           | -0.03                 |
| HD18757   | 5685                 | 4.36           | -0.29                 | HD101606  | 6134                 | 3.98           | -0.75                 | HD137052  | 6423                 | 3.94           | -0.09                 |
| HD18803   | 5658                 | 4.46           | 0.13                  | HD102574  | 6030                 | 3.92           | 0.16                  | HD139457  | 5954                 | 4.05           | -0.51                 |
| HD25621   | 6251                 | 3.95           | 0.01                  | HD106156  | 5464                 | 4.68           | 0.18                  | HD142357  | 6475                 | 3.44           | -0.02                 |
| HD28271   | 6160                 | 3.85           | -0.10                 | HD114606  | 5610                 | 4.28           | -0.48                 | HD142860  | 6286                 | 4.14           | -0.20                 |
| HD29645   | 5985                 | 4.04           | 0.06                  | HD117176  | 5527                 | 3.95           | -0.06                 | HD144284  | 6309                 | 4.13           | 0.20                  |
| HD33256   | 6242                 | 3.99           | -0.36                 | HD117361  | 6789                 | 3.95           | -0.27                 | HD145976  | 6720                 | 4.10           | 0.01                  |
| HD33608   | 6489                 | 4.08           | 0.22                  | HD120136  | 6445                 | 4.30           | 0.27                  | HD149414  | 5655                 | 4.40           | -1.31                 |
| HD35984   | 6175                 | 3.68           | -0.07                 | HD122742  | 5509                 | 4.39           | 0.00                  | HD149996  | 5662                 | 4.10           | -0.53                 |
| HD43386   | 6480                 | 4.27           | -0.06                 | HD125184  | 5659                 | 4.11           | 0.27                  | HD150012  | 6380                 | 3.80           | 0.05                  |
| HD61295   | 6987                 | 3.05           | 0.25                  | HD126512  | 5758                 | 4.05           | -0.62                 | HD151077  | 6096                 | 3.95           | -0.58                 |
| HD67228   | 5814                 | 4.00           | 0.11                  | HD126660  | 6322                 | 4.27           | -0.04                 | HD155646  | 6180                 | 3.84           | -0.13                 |
| HD76292   | 6866                 | 3.77           | -0.22                 | HD126861  | 5522                 | 4.58           | -1.18                 | HD157373  | 6427                 | 4.08           | -0.43                 |
| HD87646   | 5961                 | 4.41           | 0.30                  | HD127344  | 5651                 | 4.15           | 0.18                  | HD157856  | 6309                 | 3.93           | -0.18                 |
| HD87822   | 5697                 | 4.10           | 0.17                  | HD128167  | 6712                 | 4.32           | -0.37                 | HD159332  | 6184                 | 3.85           | -0.23                 |
| HD88986   | 5827                 | 4.13           | 0.03                  | HD128957  | 5478                 | 3.00           | -0.92                 | HD185144  | 5268                 | 4.49           | -0.23                 |
| HD91752   | 6423                 | 4.03           | -0.25                 | HD130087  | 6040                 | 4.34           | 0.26                  | HD190228  | 5306                 | 3.83           | -0.26                 |
| HD94028   | 5963                 | 4.13           | -1.43                 | HD130945  | 6431                 | 4.06           | 0.06                  | HD222404  | 4857                 | 3.23           | 0.09                  |
| HD95128   | 5861                 | 4.30           | 0.00                  | HD131156  | 5457                 | 4.52           | -0.14                 |                      |                      |                |                      |
| HD99028   | 6739                 | 3.98           | 0.06                  | HD132375  | 6273                 | 4.16           | 0.01                  |                      |                      |                |                      |

3 THE LIBRARY OF SYNTHETIC STELLAR SPECTRA

With the goal of determining the atmospheric parameters of the target stars, we need a theoretical counterpart. We adopted the library of high spectral resolution SEDs of Munari et al. (2005), which is based on the ATLAS model atmospheres of Castelli & Kurucz (2003) and covers the 2500–10500 Å wavelength range. Bertone et al. (2004) showed that ATLAS theoretical SEDs (Kurucz 1993) are suitable to match the observational spectral resolution. Theoretical spectra do not perfectly reproduce the observational system. We then degraded all the SEDs to match the observational spectral resolution with a Gaussian convolution.

4 THE SPECTROSCOPIC INDICES

In order to quantify the flux absorption of the most relevant spectral features, we considered the 41 spectral indices defined in the works of Worthey & Ottaviani (1997), Trager et al. (1998), Carretero (2007), and Lee et al. (2008) that fall within the spectral range of the observations. These indices are constructed with 3 wavelength bands: a central one, that includes the selected spectral feature, and two side bands, conveniently placed where the line blanketing is minimum, that are used to define a pseudo-continuum level. For the sake of homogeneity, we computed the values $I$ of all indices following the definition of the Lick/IDS system (Trager et al. 1998). The integrated fluxes within the side bands provide, through a linear fit, the pseudo-continuum level for the central band. The index is obtained from

$$I = \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{F_{\text{cb}}(\lambda)}{T_{\text{c}}(\lambda)} \right) d\lambda,$$

(1)

where $F_{\text{cb}}$ is the flux in the central band, whose wavelength limits are $\lambda_1$ and $\lambda_2$, and $T_{\text{c}}$ is the flux of the pseudo-continuum at the central band. All results are therefore given as a pseudo-equivalent width in angstroms.

We computed the full set of indices for all the observed stars and the synthetic SEDs of the Munari’s library. However, we made use of only 10 indices to determine the stellar parameters. We selected these 10 indices as the most promising for the determination of atmospheric parameters, as described in Sect. 4.2. We report the definition of the wavelength bands of these indices in Table 3 along with their typical error (see Sect. 4.2).

4.1 Transformation of the indices to the observational system

Theoretical spectra do not perfectly reproduce the observations (e.g. Bertone et al. 2004, 2008; Coelho 2014), as they are affected by systematic effects (physical and geometrical approximations, inaccurate atomic parameters for opacity...
Figure 2. Solar SED from the observations of the asteroids Vesta (black, upper spectrum) and Ceres (red, low spectrum). The rectangles represent the central bands of the 10 indices of Table 3.

Figure 3. SEDs of an illustrative sub-set of stars in our sample.
and \([M/H]\): for instance, in the case of the Balmer H\(_\delta\) lines, and we chose the combination that provided the best match with the accepted parameters of the Sun (\(T_{\text{eff}}, \log g, [M/H])=(5777 \text{ K}, 4.44, 0.0)\). The best result was given by the set of the following 10 indices: Ca II K30 (30), CaH, H\(\delta\)A, CN\(_1\), Ca I (4), G-whole (28), H\(\gamma\) (12), Fe4383, Ca4455, and Fe4531; they yielded, for both spectra, \((T_{\text{eff}}, \log g, [M/H])=(5750,4.50,-0.02)\).

For this set of indices, we present in Fig. 4 the plots of the theoretical vs. observed indices for the reference stars, along with the linear best fit, from which we derived the transformation equation, whose \(b\) and \(m\) parameters are given in Table 4. The two Balmer line indices and Fe4383 are already very well reproduced by the synthetic Munari’s spectra. The other indices need a larger correction to match the observations. In several cases, the linear fit crosses the bisector: this indicates that there exists a combination of photospheric parameters for which the theoretical index matches the observed one. However, these combinations strongly vary from index to index, revealing that different spectral regions (or element opacity) are better reproduced at different, for instance, \(T_{\text{eff}}\).

The transformed theoretical indices as a function of the three atmospheric parameters are depicted in Fig. 5, however, in order to understand how significant is the sensitivity of each index versus these parameters, we can compare its dynamical range with a typical error. We estimated this error with a Montecarlo method: we assumed a S/N = 50 at 4660 Å, where the line blanketing is minimum, to simulate...
late a photometric error for each synthetic spectrum of the Munari's library. For each spectrum, we run a set of 1000 realizations, where we added a randomly generated Gaussian photometric error and we computed the indices. The standard deviation of each index distribution provided the index error \( \sigma_{I_{ijk}} \) for each combination of parameters. In Table 3 we report the average error value \( \bar{\sigma}_I \) over the whole Munari's library.

A quantification of the sensitivity of an index with respect to a given atmospheric parameter is provided by the ratio between the index range in the Munari's grid and the mean of \( \sigma_{I_{ijk}} \), called throw (Worthey et al. 1994), at each mesh point of the plane formed by the other two parameters.

We present the throw of the 10 indices with respect to \( T_{\text{eff}}, \log g, \) and [M/H] in Fig. 5. We observe a variety of different behaviours: this diversity makes this combination of indices appropriate for a precise determination of the atmospheric parameters (notice, for instance, the complementarity between CN1 and G-whole (28)). The sensitivity to \( \log g \) is in general much lower than with respect to \( T_{\text{eff}} \) or [M/H]. This behaviour will reflect into a higher error in the \( \log g \) determination. However, the insensitivity to surface gravity makes some indices, as Fe4531 and Ca4455, better tools for determining the other two parameters. The highest throw is reached by H\( \delta \), CN1, and Ca II K30 (30). A peculiar property of the latter index is that it shows the higher sensitivity to metallicity at higher temperatures. Conversely, the CaH and G-whole (28) indices show a peak around solar \( T_{\text{eff}} \), while for the other indices, the sensitivity to metallicity reaches the maximum at the lower temperature edge, where the overall opacity of metal lines is generally higher. H\( \gamma \) (12) should be a very effective temperature probe, since the throw is quite constant over the whole \( \log g - [\text{M/H}] \) plane and its dependence to \( \log g \) and \( T_{\text{eff}} \) is much lower; however, the two Balmer line indices have, on average, the highest \( \log g \) throws. Furthermore, the presence of many metal lines inside
its index bands makes Hδ_A strongly sensitive to metallicity for late-G stars.

We also explored the dependence of the indices to extinction and instrumental spectral resolution, using as a reference the Munari’s synthetic spectrum (5750, 4.5, 0.0). The effect of reddening is obtained by applying the curve of Cardelli et al. (1989), increasing $A_V$ from 0 to 1 mag; and it is shown in Fig. 7. The only index that shows a variation of the same order of its typical error is G-whole(28), because its bands are defined over a wide wavelength interval (424 Å). In terms of the throw, this means that an error of 1 mag in $A_V$ estimation for a star introduces an error of $\pm 1.5$ throws.
which has to be compared with the values depicted in Fig. 6 to translate this uncertainty in terms of atmospheric parameters error. The effect of the extinction is much less for the other indices, being negligible for those defined in narrow wavelength intervals, such as Ca I(4) or Ca 4455.

Conversely, narrow band indices not affected by interstellar extinction might be subject to resolution effects. We have explored the effects of instrumental resolution by degrading the above model flux from 1.5 to 3.5 Å FWHM at a step of 0.1 Å (see Fig. 8). The most sensitive index is Ca I(4), as its bandwidths are very narrow (4 Å). Similarly, the narrow side bands (5 Å width) are also the cause of the large variation shown by Ca II K 30(30). However, the bandwidth is not the only quantity that matters, as the other index that show a change larger than its throw is CN 1, whose bands are at least 30 Å wide. In this case, the spectral morphology is also relevant since two strong feature dominated by Fe I are placed very near the limits of the central band. This property makes this index also prone to be sensitive to the precision of the wavelength calibration of observed spectra.

5 DETERMINATION OF EFFECTIVE TEMPERATURE, SURFACE GRAVITY, AND METALLICITY.

Prior to the ultimate goal, we opted to extend the grid of synthetic indices. The parameter space coverage of Munari’s library is too coarse, with steps of 250 K in $T_{\text{eff}}$, 0.5 dex in log $g$, and 0.5 dex in [M/H]. We therefore performed a trilinear interpolation of the grid of calibrated indices to significantly reduce the steps to values that are smaller than the expected errors: 5 K in $T_{\text{eff}}$, 0.05 dex in surface gravity and 0.02 dex in metallicity. This denser grid of indices includes more than 1.2 million entries.

We adopted a least squares method to determine the atmospheric parameters of the sample of target stars, by minimizing the statistic:

$$\chi^2 = \frac{1}{n} \sum_{i=1}^{n} \frac{(I_{i,\text{teo}} - I_{i,\text{obs}})^2}{\sigma_{i,\text{obs}}^2}$$

where $I_{i,\text{teo}}$ and $I_{i,\text{obs}}$ are the theoretical and the observational indices, respectively, $n$ is the total number of indices, and $\sigma_{i,\text{obs}}$ is the error associated to each index of the observed spectrum. The combination of theoretical stellar pa-
parameters, whose indices provide the minimum $\chi^2$, was assigned to the corresponding star.

A critical point in this procedure is a correct estimation of the errors $\sigma^2_{i,\text{obs}}$ in Eq. 3 since the blue interval of G-type stars is populated with thousands of non-negligible absorption lines, there is no wavelength interval, at a resolution of FWHM = 2.5 Å, where the noise can be safely measured on the observed spectra. Therefore, we devised an iterative method that includes the following steps:

(i) for each i-th index, we computed the average value of a moving standard deviation, with a 5 Å-wide window, over the whole index wavelength interval (from the bluer to the redder limit) on the observed spectrum, and we assumed this value as the estimation of the noise level. Note that, during the first iteration, the noise is definitely overestimated, because the observed spectrum contains all the absorption lines, whose contribution is minimized by using a moving standard deviation, but not completely eliminated;

(ii) the computed noise level is assumed as the standard deviation of a Gaussian distribution which is used to randomly add noise to each wavelength point inside the index interval, and then the index is calculated. This step is repeated 1000 times for each index, and we end up with distributions of index values, whose standard deviations provides $\sigma^2_{i,\text{obs}}$, which are entered in Eq. 3 to estimate the stellar parameters;

(iii) these parameters are interpolated in the Munari’s library and the corresponding spectrum is subtracted to the observed one to obtain a residual spectrum. In the ideal case, this spectrum should contain only the observational noise, but, since the synthetic spectra do not perfectly match observations, we can still expect some trace of spectral features. This is well described in Fig 9 where we show the residual spectrum, after the first iteration, for the index Fe4531 of the star BD+60 600;

(iv) the process is repeated until two consecutive iterations produce the same set of atmospheric parameters.

We used the distribution of $\chi^2$ values to estimate the error on the parameters, following Avni (1976). This is, all the combinations of parameters that have $\chi^2 < \text{MIN}(\chi^2) + 3.5$ generate a volume in the parameters space, whose extreme values along the three dimensions give the (commonly asymmetric) 68% confidence level error. The results are reported in Table 5 where we list the set of stellar parameters and the corresponding error estimates.

6 RESULTS AND COMPARISON WITH PREVIOUS WORKS

In Fig. 11 we show the distributions of the three atmospheric parameters for the 233 stars in our sample which in general appear compatible with those expected for G0–G3 stars on the main sequence. Note that the dispersion of the surface gravity distribution is quite large which, as previously pointed out, might be ascribed to the lower precision of the adopted method in determining this parameter. The average 1σ error associated to log $g$ is 0.26 dex, while it is 0.056 dex for [M/H] and 55 K for $T_{\text{eff}}$. These figures are obtained once the outliers, indicated with a shaded area in Fig. 11, are removed. We have identified as outliers the 10 objects for which the best fit described in the previous section yields a surface gravity at the lower boundary of the synthetic grid (log $g = 3.0$). Two of these outliers, TYC 4497-874-1 and BD+34 4028, have $T_{\text{eff}}$ much larger than the bulk of the sample (7000 K and 6890 K, respectively), and in fact their spectra, depicted in Fig. 11, clearly indicates that they are F or late-A stars. Their $B-V$ colors are compatible with higher temperature objects: from SIMBAD these colors are 0.45 for TYC 4497-874-1 and 0.23 for BD+34 4028, which according to the color index-spectral calibration of Pecaut, Mamajek & Bubar (2012), and assuming no extinction, would correspond to stars of types F5–F6 and A7–A8, respectively. The spectral classification of these stars, in particular that of BD+34 4028, which dates back to the early sixties (Barbier 1962), should be revisited.

It remains to be investigated the origin of the discrepancies for the rest of the deviant objects. Plausible explanations can be, among others, that we are actually dealing with binaries with composite spectra that cannot be separated at the working resolution, objects that are highly variable or that (some of) these objects are also wrongly classified. The answer is beyond the scope of this paper. For now, the parameters of the outliers should be considered as uncertain, in particular for the other 8 stars with log $g = 3.0$ dex: BD+31 3699, BD+42 384, BD+58 681, BD+60 2506, HD 105898, HD 149996, BD+45 2871 and TYC 3619-1400-1. The 10 “outliers” can be easily identified in the electronic version of Table 5 and are indicated with the symbol “*” after the stellar identification.
Figure 10. Atmospheric parameters distributions of the sample of target stars. The shaded area shows the locations of the outliers (see text). The black area shows the SMR stellar sample. For the sake of clarity, in the right panel we do not include the “outlier” BD+34 4028, for which we determined [M/H]=-2.1.

Figure 12. Top panels: Comparison of the $T_{\text{eff}}$ determined in this work and the determinations by Masana et al. (2006) (left), Bailer-Jones (2011) (middle) and Casagrande et al. (2011) (right). The solid line indicates the slope unity. In the middle panel, the filled and empty circles stand, respectively, for the results of the p and pq models of Bailer-Jones (2011). For the sake of clarity, we have incorporated in this panel a bar indicating the average value of the 90% confidence intervals reported in Bailer-Jones (2011). Bottom panels: Comparison of the log $g$ (left) and [M/H] (right) reported in Casagrande et al. (2011) and those derived in this study.
6.1 Comparison with previous works

In addition to the test with the solar spectra, a natural exercise to verify the global validity of the set of parameters we have derived is to extend the comparison with other determinations from the literature: we selected three sources that contain several of our target stars.

In the top panels of Fig. 12 we illustrate the comparison of the $T_{\text{eff}}$ for the 20 stars in common with Masana et al. (2006) (left panel), who determined this parameter from $V$ and 2MASS infrared photometry, with the study of Bailer-Jones (2011) (middle panel), who also provides $BVJHK_s$ photometric estimation of $T_{\text{eff}}$ for the objects in common (34 with his $p$-model and 37 with his $pq$-model), and with the work of Casagrande et al. (2011) (right panel), which also includes 22 stars of our sample and obtains $T_{\text{eff}}$ by means of the infrared flux method (Casagrande et al. 2006). By inspection of these figures, we can readily see that our resulting effective temperatures show, albeit some dispersion, an overall good agreement with Masana et al. (2006) and Casagrande et al. (2011), while are highly discrepant of the order of 250 K lower, when compared with the $p$-model of Bailer-Jones (2011). The disagreement cannot be explained by the fixed gravity and metallicity he used in his calculations. Bailer-Jones (2011), data are consistent with the temperature scale of Bailer-Jones et al. (1999) that indicates a temperature for a G2V star of 6015±49 K, which is more than 200 K higher than the accepted value for the Sun. Significant differences have been also found by Waite et al. (2011) for the star HIP 68328: these authors find a temperature lower by about 450 K than that of Bailer-Jones (2011), which somewhat agrees with the average difference with our results at low temperature. The comparison with the $pq$-model temperatures of Bailer-Jones (2011) shows a slightly smaller, but still systematic, offset.

For the comparison of log $g$ and [M/H], we have used the stars in common with Casagrande et al. (2011). They derive [Fe/H] from a calibration of Strömgren colors and log $g$ from the fundamental relation involving mass, $T_{\text{eff}}$, and bolometric luminosity. The comparison is depicted in the lower panels of Fig. 12 for the 22 stars that have both parameters available. The agreement is, in general, good. We have already mentioned that our gravity determinations are prone to large uncertainties, which translate in a larger dispersion of our data. However, our average log $g$ of 4.23 dex is consistent with the 4.27 dex value of Casagrande et al. (2011). Regarding metallicity, it appears that we somewhat underestimate it, as the average value of the global abundances for Casagrande et al. (2011) data and ours are, respectively, -0.02 and -0.10 dex. Nevertheless, Casagrande et al. (2011) state that their metallicity scale is 0.1 dex higher than the previous results they use for comparison.

### Table 5. Stellar atmospheric parameters. (The full version of the table is available in electronic form as Supporting Information in the online version of the article.)

| Object     | $T_{\text{eff}}$ (K) | $\sigma_{T_{\text{eff}}}$ (K) | log $g$ (dex) | $\sigma_{\log g}$ (dex) | [M/H] (dex) | $\sigma_{[M/H]}$ (dex) |
|------------|----------------------|-------------------------------|--------------|-------------------------|-------------|-----------------------|
| Vesta      | 5750                 | 35 50                         | 4.50         | 0.15                   | -0.02       | 0.04                  |
| Ceres      | 5750                 | 25 50                         | 4.50         | 0.10                   | -0.02       | 0.04                  |
| HD 236373  | 6010                 | 15 25                         | 4.50         | 0.05                   | -0.18       | 0.02                  |
| 1RXS J003845.9+332534 | 5815 | 50 50                        | 4.70         | 0.25                   | -0.26       | 0.06                  |
| [BH88] 40 1943 | 5805 | 95 140                     | 3.85         | 0.50                   | -0.30       | 0.14                  |

![Figure 13. $V$ magnitude distribution of SMR stars of this work (shaded area) and from PASTEL catalogue.](image)

#### 6.2 SMR stars

According to the results presented in Sect. 5, we identify 22 SMR stars, of which 20 are new identifications, with a global metallicity in excess of +0.16 dex, the most metallic being TYC 2655-3677-1, with $[M/H]=+0.28^{+0.04}_{-0.06}$. This sample represents about 10% of the observed targets and about the same proportion when compared with the set of stars whose average metallicity exceeds the above value in the PASTEL catalogue.

In Fig. 13, we depict the $V$ band distribution of the sample of SMR stars (shaded histogram) compared to the distribution of the 246 SMR stars present in the PASTEL catalogue. This latter sample was selected based upon these criteria: $5400<T_{\text{eff}}<6400$ K, $4.0<\log g<5.0$ dex and $[M/H]>+0.16$ dex. The number of SMR stars with $V>8$ is significantly increased, from 79 to 100, as a result of our study. The stellar parameters of SMR objects are given in Table 6.

### 7 SUMMARY

The stellar parameters ($T_{\text{eff}}$, log $g$, [M/H]) of a sample of 233 stars with spectral types between G0V-G3V were determined through the comparison of a set of spectroscopic indices and those calculated from a segment of Mu-
Table 6. Atmospheric parameters of SMR stars.

| Object          | $T_{\text{eff}}$ (K) | $\sigma_{T_{\text{eff}}}$ (K) | log $g$ (dex) | $\sigma_{\log g}$ (dex) | [M/H] (dex) | $\sigma_{[M/H]}$ (dex) |
|-----------------|----------------------|-------------------------------|--------------|-------------------------|-------------|------------------------|
| TYC 1759-462-1  | 6140                 | 80                            | 75           | 3.65                    | 0.45        | 0.40                   | 0.20 | 0.12        | 0.12 |
| BD+60 402       | 5985                 | 75                            | 70           | 4.30                    | 0.40        | 0.40                   | 0.22 | 0.08        | 0.10 |
| TYC 1230-576-1  | 5665                 | 85                            | 75           | 4.40                    | 0.35        | 0.30                   | 0.16 | 0.10        | 0.08 |
| HD 232824       | 5900                 | 50                            | 85           | 4.15                    | 0.25        | 0.45                   | 0.16 | 0.06        | 0.10 |
| HD 237200       | 6045                 | 40                            | 70           | 4.25                    | 0.25        | 0.45                   | 0.18 | 0.04        | 0.06 |
| HD 135633       | 6095                 | 65                            | 70           | 4.25                    | 0.35        | 0.45                   | 0.22 | 0.06        | 0.06 |
| BD+28 3198      | 5840                 | 25                            | 45           | 4.00                    | 0.10        | 0.25                   | 0.24 | 0.04        | 0.06 |
| Cl* NGC 6779 CB 471 | 5790           | 70                            | 65           | 3.80                    | 0.35        | 0.35                   | 0.20 | 0.10        | 0.10 |
| TYC 2655-3677-1 | 6220                 | 45                            | 50           | 4.15                    | 0.30        | 0.25                   | 0.28 | 0.04        | 0.06 |
| BD+47 3218      | 6095                 | 60                            | 45           | 4.05                    | 0.30        | 0.25                   | 0.24 | 0.04        | 0.08 |
| [M96a] SS Cyg star 14 | 6195              | 35                            | 40           | 4.00                    | 0.25        | 0.25                   | 0.24 | 0.04        | 0.06 |
| TYC 3973-1584-1 | 6000                 | 35                            | 55           | 4.45                    | 0.20        | 0.30                   | 0.20 | 0.04        | 0.06 |
| HD 228356       | 6055                 | 55                            | 20           | 4.00                    | 0.30        | 0.10                   | 0.16 | 0.06        | 0.04 |
| BD+47 3218      | 6050                 | 45                            | 60           | 4.05                    | 0.25        | 0.35                   | 0.24 | 0.04        | 0.08 |
| BD+32 3145      | 6095                 | 35                            | 50           | 3.95                    | 0.20        | 0.25                   | 0.26 | 0.06        | 0.06 |
| TYC 3986-3381-1 | 5855                 | 55                            | 60           | 4.15                    | 0.25        | 0.25                   | 0.26 | 0.06        | 0.06 |
| TYC 3982-2812-1 | 5805                 | 60                            | 50           | 4.30                    | 0.30        | 0.25                   | 0.18 | 0.06        | 0.06 |
| TYC 3618-1191-1 | 5940                 | 60                            | 60           | 4.40                    | 0.35        | 0.30                   | 0.24 | 0.08        | 0.08 |
| TYC 3986-758-1  | 5845                 | 55                            | 65           | 4.05                    | 0.30        | 0.35                   | 0.16 | 0.06        | 0.08 |
| HD 283538       | 6055                 | 35                            | 60           | 3.95                    | 0.10        | 0.30                   | 0.20 | 0.06        | 0.08 |
| HD 137510       | 5875                 | 70                            | 20           | 4.00                    | 0.35        | 0.05                   | 0.16 | 0.08        | 0.04 |
| HD 212809       | 5975                 | 60                            | 50           | 4.55                    | 0.30        | 0.25                   | 0.16 | 0.04        | 0.06 |

Acknowledgments

R.L.V, E.B. and M.C. want to thank CONACyT for financial support through grants SEP-2009-134985 and SEP-2011-169554. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Adibekyan, V. Z., Santos, N. C., Sousa, S. G., & Israeli, G. 2011, A&A, 535, L11
Gonzalez, G. 1998, A&A, 334, 221
Harlan, E. A., & Taylor, D. C. 1970, AJ, 75, 165
Heiter, U., Soubiran, C., Netopil, M., & Paunzen, E. 2014, A&A, 561, A93
Kurucz, R. 1993, SYNTHE Spectrum Synthesis Programs and Line Data. Kurucz CD-ROM No. 18. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993., 18
Lee, Y.S., Beers, T.C., Sivarani, T., et al. 2008, AJ, 136, 2022
Liu, G. Q., Deng, L., Chávez, M., et al. 2008, MNRAS, 390, 665
Masana, E., Jordi, C., & Ribas, I. 2006, A&A, 450, 735
Molenda-Zakowicz, J., Sousa, S. G., Frasca, A., et al. 2013, MNRAS, 434, 1422
Munari, U., Sordo, R., Castelli, F., & Zwitter, T. 2005, A&A, 442, 1127
Neves, V., Santos, N. C., Sousa, S. G., Correia, A. C. M., Israelian, G. 2009, A&A, 497, 563
Pecaut, M., Mamajek, E., Bubar, E. J. 2012, ApJ, 746, 154.
Porto de Mello, G. F., da Silva, R., da Silva, L., & de Nader, R. V. 2014, A&A, 563, A52
Rich, R.M. 1988, AJ, 95, 828
Santos, N. C., Israelian, G., & Mayor, M. 2001, A&A, 373, 1019
Santos, N. C. 2008, in The Metal-Rich Universe, ed. G. Israelian & G. Meynet. Cambridge Univ. Press, Cambridge, p. 17
Soubiran, C., Le Campion, J.-F., Cayrel de Strobel, G., & Caillo, A. 2010, A&A, 515, A111
Spinrad, H., & Taylor, B.J. 1969, ApJ, 157, 1279
Taylor, B. J. 1996, ApJS, 102, 105
Trager, S.C., Worthey, G., Faber, S.M., Burstein, D., & Gonzalez, J.J. 1998, ApJS, 116, 1
Waite, I. A., Marsden, S. C., Carter, B. D. et al., 2011, Publications of the Astronomical Society of Australia, 28, 323
Worthey, G., & Ottaviani, D.L. 1997, ApJS, 111, 377
Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, ApJS, 94, 687

This paper has been typeset from a TeX/ L\TeX file prepared by the author.