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FUNDPAR: A PROGRAM FOR DERIVING FUNDAMENTAL PARAMETERS FROM EQUIVALENT WIDTHS

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RESUMEN

Implementamos un programa en Fortran que determina parámetros fundamentales de estrellas de tipo solar, a partir de anchos equivalentes del Fe. La solución debe verificar tres condiciones en el método estándar: equilibrio de ionización, equilibrio de excitación e independencia entre abundancias y anchos equivalentes. Calculamos modelos de atmósfera de Kurucz con opacidades NEWODF. Detalles como el parámetro de longitud de mezcla, el sobre impulso convectivo, etc. se calculan con un programa independiente. FUNDPAR calcula las incertezas por dos métodos: el criterio de Gonzalez & Vanture (1998) y utilizando la función χ^2. Los resultados derivados con FUNDPAR están de acuerdo con determinaciones previas en la literatura. En particular obtuvimos parámetros fundamentales de 58 estrellas con exoplanetas. El programa está disponible en la red[1].

ABSTRACT

We implemented a Fortran code that determines fundamental parameters of solar type stars from a list of Fe line equivalent widths. The solution should verify three conditions in the standard method: ionization equilibrium, excitation equilibrium and independence between metallicity and equivalent widths. Solar-scaled Kurucz model atmospheres with NEWODF opacities are calculated with an independent program. Parameter files control different details, such as the mixing-length parameter and the overshooting. FUNDPAR derives the uncertainties following two methods: the criterion of Gonzalez & Vanture (1998) and the dispersion using the $\chi 2$ function. The code uses the 2009 version of the MOOG program. The results derived with FUNDPAR are in agreement with previous determinations in the literature. The program is freely available from the web[1].

Key Words: stars: abundances — stars: fundamental parameters

1. INTRODUCTION

Different methods have been used in the literature to derive fundamental parameters and metallicities of solar type stars. For instance, some studies begin with a photometric estimation of temperature and gravity and then derive the metallicity using equivalent widths. Useful codes such as WIDTH9 (Kurucz 1993; Kurucz 1995, private communication) or BLACKWEL[2] (an implementation of the Blackwell method) are widely used in the literature (e.g., Saffe & Levato 2004). However, the temperature and gravity are usually considered as fixed parameters. The observed stellar spectra could be compared with a grid of previously calculated synthetic spectra (e.g., Fischer & Valenti 2005; Saffe et al. 2008) to determine fundamental parameters. However, in this case the instrumental broadening should be taken into account and the rotational velocity could be considered as another independent parameter.

Recently, Sousa et al. (2010) derived an effective temperature calibration based on line equivalent width ratios of different absorption lines. Also, the equivalent widths of Fe lines could be used to determine the parameters of solar type stars. The solution should verify three conditions in the standard

[1] `http://icate-conicet.gob.ar/saffe/fundpar/`.

[2] `http://www1.appstate.edu/dept/physics/spectrum/spectrum.html`.

method: [FeI/H]=[FeII/H] (i.e., ionization equilibrium), independence between the metallicity and both the excitation potential (i.e., excitation equilibrium) and the equivalent widths. This method has been applied to solar type stars, for instance, in the determination of metallicity of stars with and without low mass companions or exoplanets (e.g., Gonzalez 1997, 1998; Gonzalez, Wallerstein, & Saar 1999; Santos, Israelian, & Mayor 2000; Gonzalez & Laws 2000; Gonzalez et al. 2001; Laws & Gonzalez 2001; Laws et al. 2003). The process estimate initially the fundamental parameters ($T_{\rm eff}$, $\log g$, [Fe/H] and ξ, the microturbulence velocity). This information is used in the ATLAS program (Kurucz 1993; Kurucz 1995, private communication) to derive a model atmosphere in LTE (local thermodynamic equilibrium). The model atmosphere with the measured equivalent widths of the spectra, is introduced in the code MOOG[4] to derive a new metallicity. If the mentioned conditions are not satisfied, the process is restarted using new fundamental parameters calculated with the downhill method.

In this contribution, we present the Fortran code FUNDPAR (and their complement `atlas.launcher`) that implements the method explained above. The programs are available from the Web[5], including detailed installation instructions and some technical details such as the format of the input/output files (`install.txt`). As an example of practical use, we derived the fundamental parameters of 58 main sequence exoplanet host stars and verified the metal-rich nature of the group. The values derived are in agreement with previous determinations from the literature.

In § 2 we show the general idea and the logic of the program. The procedure of minimization of the χ^2 function is detailed in § 3. The estimation of the uncertainties in the parameters and the comparison with literature, are showed in §§ 4 and 5, respectively. Finally we present some concluding remarks in § 6.

2. THE LOGIC OF THE PROGRAM

The algorithm is organized in one main procedure and a number of sub-programs with specific tasks. The iterative process begins at one starting point in a 4D-space, where the variables are ($T_{\rm eff}$, $\log g$, [Fe/H], ξ). This starting point could be optionally given in the first line of the input file (see the file `install.txt` for details of input/output files). If this point is unknown, the program adopts (5000 K, 4.00 dex, -0.10 dex, 1.00 km s^{-1}) to begin the iteration. For example, Santos et al. (2000) estimate $T_{\rm eff}$ and $\log g$ from the *uvby* photometry and the calibration of Olsen (1984), while [Fe/H] and ξ are estimated following Schuster & Nissen (1989) and Edvarsson et al. (1993), respectively.

Then for each iteration step, i.e., for each group of 4 parameters ($T_{\rm eff}$, $\log g$, [Fe/H], ξ), the program should:

(a) Generate an appropriate ATLAS model atmosphere (through the `atlas.launcher` program). First, the code should select from the Kurucz grid the model atmosphere closest in the parameter space to those requested and take this as initial input model. Then the program executes ATLAS9 to derive the final model.

(b) Transform the model atmosphere to a format readable by MOOG (subroutine `kurucz2moog`). The format of the model atmosphere used by MOOG is not exactly the Kurucz model and should be rewritten accordingly.

(c) Call the MOOG program. At this point, the program takes the file containing the equivalent widths of the FeI and FeII lines of the star and the model atmosphere as input for the MOOG program. The MOOG program is executed using a driver called "abfind" which is selected for the abundance determination.

(d) Read the new metallicity values calculated by MOOG (subroutine `rmr, read-moog-results`); and finally,

(e) Determine the value of the χ^2 function. This step will be explained below.

We take into account the conditions mentioned in the introduction through a variable called χ^2. We adopt for χ^2 the expression $\chi^2 = w_1 c_1^2 + w_2 c_2^2 + w_3 c_3^2 + w_4 c_4^2$, where w_1,...,w_4 are weight factors ($w_i \geq 0$), c_1 and c_2 are the slopes in the plots of [Fe/H] vs. $\log_{10}$(W/λ) (logarithm of the reduced equivalent width) and [Fe/H] vs. excitation potential, c_3 = [FeI/H] $-$ [FeII/H], and c_4 is the difference between the input ATLAS metallicity (Step a) and the resulting metallicity using equivalent widths (Step d). We added explicity the fourth condition: the input metallicity of the model atmosphere should be similar to the output metallicity derived from equivalent widths, i.e., the term with c_4. Then, the four conditions are quantified in the χ^2 function: the solution corresponds to the minimum value of χ^2.

[4] http://verdi.as.utexas.edu/moog.html.

[5] http://icate-conicet.gob.ar/saffe/fundpar/.

TABLE 1

SAMPLE OF THE FUNDPAR.PAR FILE WHICH CONTAINS THE WEIGHTS OF THE χ^2 FUNCTION

t1 = 200.00	# Characteristic length scale of Teff (K)
t2 = 0.10	# Characteristic length scale of Logg (dex)
t3 = 0.10	# Characteristic length scale of [Fe/H] (dex)
t4 = 0.10	# Characteristic length scale of Xita (km s^{-1})
w1 = 25000.00	# Chi2 Weight factor
w2 = 2500.00	# Chi2 Weight factor
w3 = 1111.00	# Chi2 Weight factor
w4 = 1111.00	# Chi2 Weight factor

The users are free to modify the values of the weights w_1,...,w_4 according to their own criteria. However, we show a simple example estimating aproximately the values of the weights. Adopting $\chi^2 = 1$ as the limiting case of a solution, each condition contributes, for example, with 0.25 to the sum $\chi^2 = 0.25 + ... + 0.25$. In this case the 4 conditions are taken equally important within χ^2, which is not always true. In the plot of abundance vs. excitation potential, we accept a maximum slope, for instance, of $c_1 \sim 0.015/4$ dex/eV, taking a difference of $\sim$0.015 dex in the abundance, for a total range of $\sim$4 eV in the excitation potential of Fe lines. Then, in the limiting case, $w_1 c_1^2 \sim 0.25$ and thus $w_1 \sim 18000$ eV^2/dex^2. The units of w_1 are forced so as to obtain a dimensionless product $w_1 c_1^2$. In the plot of abundance vs. $\log_{10}$(W/λ) (where W and λ are the equivalent width and wavelength in Å, respectively), we accept a maximum slope (for example) of $c_2 \sim 0.015/1.5$, taking a difference of 0.015 dex in the abundance for a range of $\sim$1.5 in the $\log_{10}$(W/λ) of Fe lines. Then, $w_2 c_2^2 \sim 0.25$ and thus $w_2 \sim 2500$. For the third condition, c_1 = [FeI/H] − [FeII/H] and we adopt a maximum difference of 0.015 dex. Then, $w_3 c_3^2 \sim 0.25$ and thus $w_3 \sim 1100$ dex^{-2}. Similarly, for w_4 result $w_4 \sim 1100$ dex^{-2}. In this estimation the weights w_1,...,w_4 turned out to be 18000 eV^2/dex^2, 2500, 1100 dex^{-2} and 1100 dex^{-2}, respectively, for a solution in which the four conditions contribute equally with 0.25 to the χ^2 function in the limiting case of $\chi^2 = 1$. In this example those solutions with $\chi^2 > 1$ do not verify the four conditions.

The user will probably have his/her own criteria for the values of w_1,...,w_4, instead of the values of the example explained the previous paragraph. The user is free to modify the values of w_1,...,w_4 (file `fundpar.par`) and this could result in more (or less) restrictive conditions. The code uses these values to define χ^2 and then search for the minimum of the function. Then, the user should read the values of the slopes and metallicities in the output files to verify if the four conditions are satisfied. The values of w_1,...,w_4 previously shown seem to verify in practice the requirements of minimization and verification of the four conditions. In Table 1 we show a sample of the file `fundpar.par` where the weights could be modified. Other parameters will be explained in the following sections.

According to the definition, χ^2 could be considered as a function that depends on the fundamental parameters $\chi^2 = \chi^2(T_{\rm eff},\ \log g,\ [\mathrm{Fe/H}],\ \xi)$. If χ^2 is not a minimum, the algorithm should determine the next set of four possible values. These new variables are used in another iteration (following Steps a to e) to derive a new model atmosphere, metallicity and, finally, a new value of χ^2. The algorithm that determines the next group of four parameters is called the downhill method, and explained in the next section.

In Table 2 we show a list of the input and output files used by FUNDPAR. The format of the input/output files is detailed in the file `install.txt`. There are two main directories (`datain` and `dataout`) containing the input and output files of the stars. The equivalent widths should be stored in separate files (one file per star), and the names of these files should be listed in another file called `filenames.txt`. The files `atlas.par`, `batch.par` and `fundpar.par` contain the values of some parameters used in the model calculation and abundance determination and will be explained in the next sections. After the execution of FUNDPAR, three output files per star are created: the ATLAS model atmosphere of the solution and two output files directly from the MOOG abundance de-

TABLE 2

LIST OF THE INPUT AND OUTPUT FILES USED BY FUNDPAR

Filename	Directory	Comment
Input Files:		
`filenames.txt`	`datain`	List of files containing the equivalent widths
`hd001.txt`	`datain`	Equivalent widths of the star HD 001
...	...	...
`hd999.txt`	`datain`	Equivalent widths of the star HD 999
Parameter Files:		
`atlas.par`	`atlas.launcher`	Parameters used by ATLAS
`batch.par`	FUNDPAR	Parameters used by MOOG
`fundpar.par`	FUNDPAR	Parameters used by FUNDPAR
Output Files:		
`hd001.mod`	`dataout`	Model atmosphere of HD 001 from ATLAS9
`hd001.out1.txt`	`dataout`	Output file 1 from MOOG
`hd001.out2.txt`	`dataout`	Output file 2 from MOOG
...	...	...
`output1.screen`	`dataout`	Similar output to the screen
`output2.results`	`dataout`	Table of results for all the stars

termination. The file `output1.screen` displays similar information on the screen and `output2.results` lists the final parameters and their uncertainties.

3. THE DOWNHILL SIMPLEX METHOD: MINIMIZATION OF χ^2

In this section we briefly review the minimization procedure for χ^2 as a function of four independent variables, using a Numerical Recipes routine called `amoeba` (Press et al. 1992). The downhill simplex method is due to Nelder & Mead (1965) and requires only function evaluations, not derivatives. A simplex could be considered to be a geometrical figure of $N+1$ vertices in N-dimensional space (in our case, $N = 4$). Taking any vertex as the origin, then the four other points define possible vector directions in the 4-dimensional volume.

The downhill simplex method starts with a group of $N + 1$, i.e., 5 vertices rather than a single point or vertex. These vertices are displaced with a scale length characteristic of the problem. In our case, χ^2 is initially calculated adopting displacements of 200 K, 0.1 dex, 0.1 dex and 0.1 km s^{-1} for the variables $T_{\rm eff}$, $\log g$, [Fe/H] and ξ, respectively. The characteristic lengths could be modified in the file `fundpar.par` (see Table 1). FUNDPAR executes an initial calculation of χ^2 at the vertices of the simplex, before the iteration process begins. Then, the downhill method takes a series of steps, usually moving the highest point of the simplex, i.e., where χ^2 is maximum. Succesive steps could be visualized as reflections, expansions and contractions of the 4-dimensional object. When the simplex finds a valley, it contracts itself down the valley. An appropriate sequence of these steps will converge to the minimum of χ^2.

As explained by Press et al. (1992), the termination criterion is usually delicate in the minimization process. The program requires that the decrease in the function value in the terminating step be fractionally smaller that some tolerance (variable `ftol` within the `amoeba` subroutine). The method just described exactly follows Nelder & Mead (1965). However, in practice we found that for some stars the routine converges in a few iteration steps to a solution with $\chi^2 \gg 1$. In such cases the code decreases the tolerance and continues the iteration process from the last point. We verified that it is not necessary in this case to restart the process, because the effect of modifying the tolerance determines only at which iteration the program stops. We also note that decreasing the tolerance does not guarantee convergence of the solution: we are only modifying the termination step or the termination criterion.

With the adopted values of w_1,...,w_4, the program usually takes less than ∼200 iterations to reach a solution. The number of iterations is a known

TABLE 3

PARAMETERS ADOPTED IN DIFFERENT CASES (A,...,E) FOR 5 SAMPLE STARS (SEE TEXT FOR DETAILS)

Run	ML	W	D
A	1.25	1	2
B	1.25	0	2
C	1.32	1	2
D	1.25	1	1
E	1.25	1	0

problem of the downhill method. If the code reaches a solution with $\chi^2 > 1$, then the program restarts the iteration process using the last solution as a new initial condition. The restart is recomended by Press et al. (1992) in the downhill method to eliminate a probable local minimum of the function. The code restarts the iteration process only once. The user also could manually restart the process using the last solution, for instance, as the new initial condition and FUNDPAR will try to reach a solution with a smaller χ^2.

4. DERIVATION OF THE MODEL ATMOSPHERES

Together with the FUNDPAR code, we provide another independent program called `atlas.launcher`, which prepares and executes the Kurucz's ATLAS9 in LTE. As input of `atlas.launcher` the fundamental parameters $T_{\rm eff}$, $\log g$, [Fe/H] and ξ are used. The output is an ATLAS solar-scaled model atmosphere corresponding to these parameters. The program uses a parameter file called `atlas.par` that contains different parameters used by ATLAS, such as the mixing-length parameter (usually taken as 1.25), and the overshooting weight parameter W, defined in Castelli, Gratton, & Kurucz (1997). A list of files used by ATLAS (grid of precalculated models, Rosseland and ODFs, and a sample of `atlas.par`) is presented in the file `install.txt`.

Then, the model atmosphere and the equivalent widths are introduced in the MOOG program. We incorporated in this code the solar abundances of Grevesse & Sauval (1998) instead of the original from Anders & Grevesse (1989), except for Fe for which we adopted [Fe/H]=7.47 dex. The NEWODF opacities use these abundance values (Castelli & Kurucz 2003). MOOG use a parameter file (`batch.par`) where some options[6] could be modified, such as the molecular equilibrium and the van der Waals line damping options.

Literature authors have different preferences for the choice of ATLAS and MOOG parameters. The user is free to modify the parameters according to his/her own criteria, and then FUNDPAR will find the corresponding solution. To give an idea of the sensivity of the results, we rederived the fundamental parameters of 5 sample stars (HD 106252, HD 177830, HD 190228, HD 195019 and HD 202206) using different combinations of the parameters. In the Table 3 we show the values of the parameters adopted in different calculations A,...,E. The parameters shown are the mixing-length parameter (ML), the overshooting parameter (W) and the line damping option (D). We start the execution of case A adopting ML=1.25, W=1 and D=2. In case B we switched off the overshooting, while in case C we adopted a slightly higher ML. In cases D and E we used different options for the line damping.

The variation of $T_{\rm eff}$, $\log g$, [Fe/H] and ξ (adopting different ML, W and D) is different from star to star. For instance, varying W increases the $T_{\rm eff}$ for some stars, and decreases it for others. Probably the variation depends on the fundamental parameters of the stars. Then, in the Figure 1 we show the difference (called Δ) between the parameters derived for case A and the parameters derived for cases B, C, D and E. The differences are plotted vs. $T_{\rm eff}$ only for the 5 stars previously mentioned. All differences are derived with respect to case A. The symbols used in the panels are filled circles (results B-A), diagonal crosses (results C-A), empty circles (results D-A) and squares (results E-A). The panels seems to show a slight dependency on $T_{\rm eff}$. Switching on/off the overshooting (case B), $\Delta T_{\rm eff}$, $\Delta \log g$ and Δ[Fe/H] seem to show a dependency on $T_{\rm eff}$. Increasing ML from 1.25 to 1.32 (case C), we find no clear tendency and the differences are small. Using the damping option 1 instead of 2 (case D), $T_{\rm eff}$, $\log g$ and [Fe/H] increase by an average of $\sim$48 K, $\sim$0.14 dex and $\sim$0.05 dex, respectively. Using the damping option 0 (case E), $T_{\rm eff}$, $\log g$, [Fe/H] and ξ increase by an average of $\sim$70 K, $\sim$0.20 dex, $\sim$0.06 dex and $\sim$0.1 km s^{-1}, respectively. We caution that these preliminary differences have been derived using only 5 stars. A larger number of stars is needed to properly determine how the parameters ML, W and D modify the derived fundamental parameters.

[6]For a complete list of options, see the manual of the MOOG program, `http://verdi.as.utexas.edu/moog.html`.

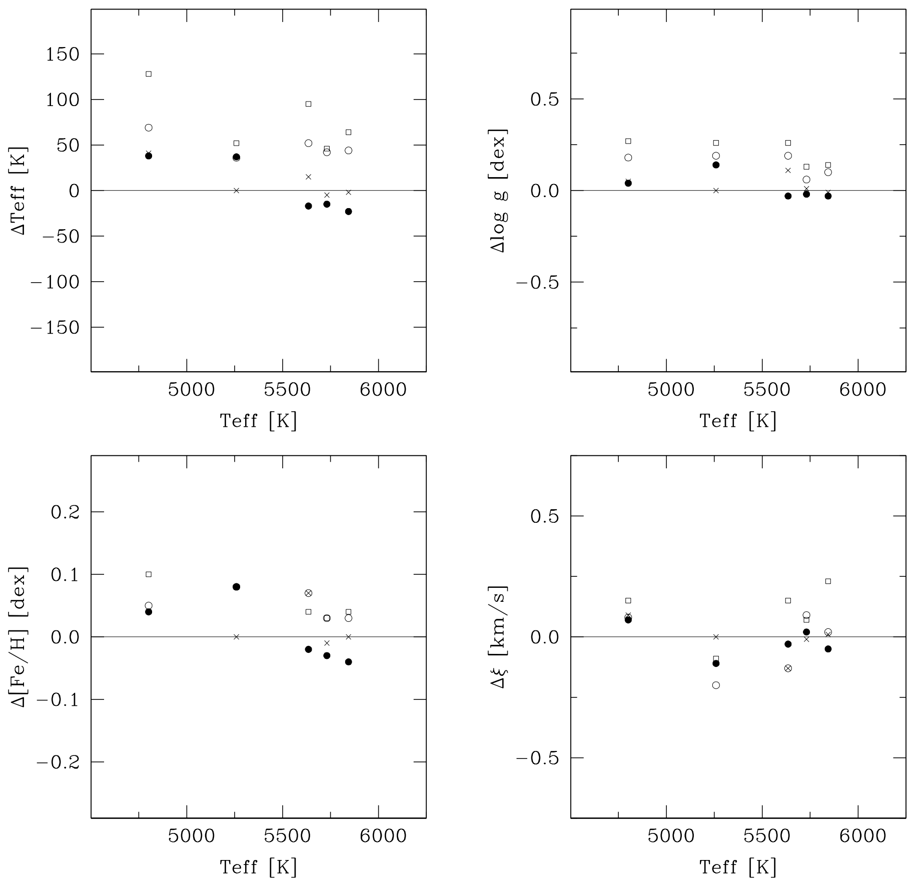

Fig. 1. Difference between the parameters derived in case A and the parameters derived in cases B, C, D and E. The differences are plotted vs. $T_{\rm eff}$ only for 5 stars. For instance, in the $T_{\rm eff}$ panel we ploted $\Delta T_{\rm eff} = T_{\rm eff}({\rm B}) - T_{\rm eff}({\rm A})$ with filled circles. The symbols used in the panels are filled circles (differences B-A), diagonal crosses (differences C-A), empty circles (differences D-A) and squares (differences E-A).

5. UNCERTAINTY ESTIMATION OF THE DERIVED PARAMETERS

The uncertainties in the atmospheric parameters were estimated following Gonzalez & Vanture (1998). The uncertainty in ξ was determined from the standard deviation of the slope of the least-squares fit of abundance vs. reduced equivalent width. Then, the dispersion of the effective temperature was determined from the uncertainty of the slope of the least-squares fit of abundance vs. excitation potential, in addition to the uncertainty of the slope due to the uncertainty of ξ. The uncertainty of the Fe abundance was derived combining the uncertainties of $T_{\rm eff}$, ξ and the scatter of the individual FeI abundances (standard deviation of the mean), all added in quadrature. In calculating the uncertainty of $\log g$, we include the contribution from the uncertainty of $T_{\rm eff}$ in addition to the scatter in the FeII line abundances.

We derive another estimation of the uncertainty of the solution using χ^2. As we explained previously, we select the values of the weights such that solutions with $\chi^2 > 1$ do not verify the four conditions. Then, we adopt the size of the region $\chi^2 = 1$ as another estimation of the uncertainty of the solution. FUNDPAR stores a record of the points with $\chi^2 < 1$ and uses them to estimate the size of the region. The range of the values of $T_{\rm eff}$, $\log g$, [Fe/H] and ξ is shown in the results along with the number n of solutions with $\chi^2 < 1$. These dispersion values should be taken with caution if n is small. This kind of uncertainty is comparable to those derived by the criteria of Gonzalez & Vanture (1998). In the next section we present a histogram comparing both uncertainties for a group of exoplanet host stars. The user is free to select among them, or to take the maximum value, for instance.

TABLE 4

FUNDAMENTAL PARAMETERS AND DISPERSIONS DERIVED WITH FUNDPAR

Star	$T_{\rm eff}$ [K]	$\log g$ [dex]	[Fe/H] [dex]	ξ [km s^{-1}]	e$T_{\rm eff}$ [K]	elog g [dex]	e[Fe/H] [dex]	eξ [km s^{-1}]	Ref[1]
14 Her	5294	4.33	0.50	0.71	40.60	0.19	0.07	0.05	R1
16 Cyg A_1	5704	4.29	−0.01	1.32	90.75	0.19	0.11	0.10	R2
16 Cyg A_2	5749	4.23	0.07	1.02	15.58	0.04	0.06	0.03	R3
16 Cyg B_1	5632	4.36	−0.05	1.21	83.68	0.25	0.10	0.09	R2
16 Cyg B_2	5690	4.30	0.05	0.91	14.16	0.04	0.06	0.03	R3
47 Uma	5720	4.26	−0.12	1.31	86.63	0.15	0.10	0.08	R2
51 Peg_1	5681	4.37	0.11	1.21	62.21	0.11	0.08	0.08	R2
51 Peg_2	5797	4.39	0.22	1.13	16.33	0.04	0.04	0.03	R4
70 Vir	5481	3.98	−0.08	1.10	92.16	0.15	0.09	0.07	R2
BD-10 3166	5275	4.36	0.32	0.69	42.70	0.05	0.09	0.05	R4
HD 106252	5844	4.50	−0.06	0.98	12.23	0.12	0.05	0.03	R5
HD 10697	5600	3.96	0.10	1.20	28.41	0.03	0.05	0.04	R4
HD 108147	6279	4.59	0.19	1.11	41.51	0.12	0.11	0.09	R5
HD 114783	5100	4.48	0.08	0.87	15.70	0.10	0.07	0.04	R5
HD 117176	5487	4.09	−0.06	1.00	10.86	0.10	0.06	0.02	R5
HD 1237_1	5537	4.50	0.22	1.19	30.76	0.15	0.07	0.05	R4
HD 1237_2	5468	4.50	0.05	1.38	23.27	0.18	0.07	0.04	R6
HD 12661_1	5670	4.41	0.38	0.91	19.18	0.06	0.05	0.03	R4
HD 12661_2	5719	4.48	0.38	0.84	24.28	0.04	0.05	0.04	R4
HD 13445	5080	4.43	−0.30	0.65	19.69	0.23	0.07	0.05	R6
HD 134987	5719	4.28	0.33	1.09	22.44	0.04	0.07	0.04	R4
HD 136118	6153	4.37	−0.09	2.00	21.82	0.15	0.08	0.11	R5
HD 141937	5832	4.50	0.12	0.97	12.63	0.10	0.05	0.03	R5
HD 160691	5788	4.49	0.24	1.12	22.03	0.08	0.06	0.04	R5
HD 16141_1	5768	4.24	0.17	1.10	22.07	0.04	0.04	0.04	R4
HD 16141_2	5751	4.28	0.16	1.00	12.18	0.05	0.05	0.03	R5
HD 168443	5549	4.13	0.08	1.04	17.06	0.02	0.06	0.03	R4
HD 168746	5566	4.43	−0.09	0.94	10.51	0.04	0.05	0.03	R5
HD 169830_1	6268	4.10	0.20	1.29	22.14	0.18	0.05	0.03	R6
HD 169830_2	6283	4.23	0.16	1.27	24.27	0.08	0.06	0.06	R5
HD 177830	4801	3.37	0.38	0.95	55.16	0.07	0.10	0.04	R4
HD 187123	5792	4.39	0.14	1.04	26.26	0.08	0.04	0.04	R1
HD 190228	5259	3.64	−0.32	1.13	11.79	0.11	0.05	0.02	R5
HD 192263	4905	4.38	−0.02	0.73	19.76	0.18	0.08	0.05	R4
HD 195019a	5731	4.17	0.00	1.20	13.09	0.13	0.05	0.03	R5
HD 19994.2	6147	4.35	0.12	2.03	23.94	0.10	0.08	0.09	R5
HD 202206_1	5635	4.55	0.28	0.88	24.27	0.14	0.06	0.04	R6
HD 202206_2	5713	4.45	0.30	1.07	14.42	0.04	0.06	0.03	R5
HD 209458	6065	4.43	0.02	1.14	18.56	0.13	0.06	0.04	R4
HD 210277	5517	4.34	0.24	0.84	26.56	0.12	0.05	0.04	R1
HD 217107	5602	4.42	0.42	0.87	17.64	0.03	0.05	0.03	R4
HD 22049	5083	4.47	−0.14	0.84	14.29	0.15	0.06	0.04	R5
HD 222582	5719	4.25	0.00	0.99	18.90	0.03	0.04	0.04	R4
HD 27442	4859	3.60	0.38	1.21	45.85	0.22	0.15	0.06	R5
HD 28185	5637	4.54	0.21	0.96	13.79	0.04	0.06	0.03	R5
HD 33636	5877	4.27	−0.13	0.95	14.81	0.10	0.06	0.04	R5
HD 37124_1	5579	4.60	−0.39	0.74	19.83	0.11	0.09	0.08	R5
HD 37124_2	5495	4.46	−0.42	0.71	22.54	0.04	0.05	0.07	R4
HD 38529	5600	3.82	0.34	1.25	38.21	0.05	0.06	0.03	R4
HD 4203	5667	4.43	0.43	1.08	29.95	0.06	0.15	0.06	R5
HD 4208	5592	4.33	−0.29	0.87	14.74	0.15	0.06	0.04	R5

TABLE 4 (CONTINUED)

Star	$T_{\rm eff}$ [K]	$\log g$ [dex]	[Fe/H] [dex]	ξ [km s^{-1}]	e$T_{\rm eff}$ [K]	elog g [dex]	e[Fe/H] [dex]	eξ [km s^{-1}]	Ref[1]
HD 46375_1	5210	4.37	0.24	0.65	35.26	0.10	0.06	0.04	R4
HD 46375_2	5252	4.50	0.26	0.68	21.15	0.09	0.10	0.06	R5
HD 50554	5978	4.51	−0.01	1.10	11.93	0.10	0.06	0.03	R5
HD 52265_1	6102	4.28	0.24	1.20	17.71	0.06	0.05	0.03	R4
HD 52265_2	6163	4.37	0.27	1.21	19.51	0.10	0.03	0.03	R4
HD 52265_3	5993	4.21	0.17	1.24	25.17	0.18	0.06	0.04	R6
HD 6434	5715	4.32	−0.54	0.70	23.11	0.16	0.11	0.10	R5
HD 68988	5936	4.49	0.32	1.19	19.40	0.02	0.09	0.05	R5
HD 75289_1	6138	4.52	0.27	1.50	20.96	0.10	0.07	0.05	R7
HD 75289_2	6070	4.44	0.23	1.42	30.93	0.16	0.06	0.05	R6
HD 75332	6277	4.47	0.22	1.03	24.73	0.11	0.05	0.04	R4
HD 82943_1	5950	4.45	0.28	1.10	25.37	0.07	0.05	0.03	R6
HD 82943_2	5987	4.46	0.24	1.11	17.85	0.04	0.05	0.03	R5
HD 83443_1	5389	4.31	0.33	1.00	27.40	0.18	0.08	0.04	R6
HD 83443_2	5427	4.40	0.34	0.99	22.07	0.13	0.07	0.05	R5
HD 8574	6029	4.34	0.00	1.19	13.29	0.16	0.05	0.03	R5
HD 89744	6315	4.16	0.27	1.67	28.06	0.07	0.04	0.05	R4
HD 92788	5755	4.43	0.29	1.02	26.37	0.04	0.05	0.04	R4
HD 95128	5832	4.31	0.02	1.08	13.83	0.10	0.05	0.02	R5
HR 810	6072	4.48	0.15	1.23	27.89	0.09	0.07	0.08	R4
ν And_1	6165	4.21	0.13	1.40	50.44	0.03	0.06	0.07	R8
ν And_2	6150	4.14	0.09	1.48	50.48	0.03	0.07	0.07	R7
ρ Cnc_1	5201	4.27	0.32	0.78	99.87	0.20	0.11	0.10	R2
ρ Cnc_2	5206	4.40	0.41	0.69	27.42	0.18	0.07	0.04	R7
ρ Crb	5751	4.15	−0.24	1.33	28.85	0.05	0.04	0.05	R2
τ Boo_1	6517	4.37	0.30	1.57	60.99	0.04	0.06	0.08	R8
τ Boo_2	6415	4.23	0.30	1.34	49.61	0.06	0.08	0.07	R7

[1]References for the equivalent widths (last column): R1: Gonzalez et al. (1999), R2: Gonzalez (1998), R3: Laws & Gonzalez (2001), R4: Gonzalez et al. (2001), R5: Laws et al. (2003), R6: Santos et al. (2000), R7: Gonzalez & Laws (2000), R8: Gonzalez (1997).

FUNDPAR include the uncertainty estimation of the parameters and they are shown in the ouput files. The size of the uncertainty depends on many factors, such as the number of lines involved (which is usually small for FeII), the measured equivalent widths and the laboratory data of the spectral lines. The $\log gf$ values (oscillator strength) and excitation potential of the lines are important because many derived values (Fe abundances, the slopes of abundance vs. equivalent widths and vs. excitation potential, etc.) depend on these quantities. We note that the inclusion of a line which (for one reason or another) implies an abundance very different from the average could modify the results and/or increase the uncertainty of the parameters. These lines should be eliminated from the list of measured equivalent widths. The abundances of individual lines are shown in the file `out2.txt` (`work.dir` directory).

6. COMPARISON WITH LITERATURE VALUES

There are small differences in the parameters derived using this method by different authors. Santos et al. (2000) derived surface gravities systematically larger than the ones obtained by other authors (e.g., Gonzalez et al. 2001) by 0.15 dex. To solve this problem, Santos, Israelian, & Mayor (2004) adopted new $\log gf$ values for the iron lines. Then the authors found a small average difference of +25 K in the temperature compared to the studies of Gonzalez et al. (2001) and Laws et al. (2003) (57 stars in common). Also their $\log g$ are +0.05 dex (on average) larger and the average differences in metallicity are between −0.10 and +0.10 dex. Ammler-von Eiff et al. (2009) derived the fundamental parameters of host stars with transiting planets using the 2002 version of the code MOOG and ATLAS model atmospheres. However, for the TrES and HAT objects the abundances determined by Sozzetti et al.

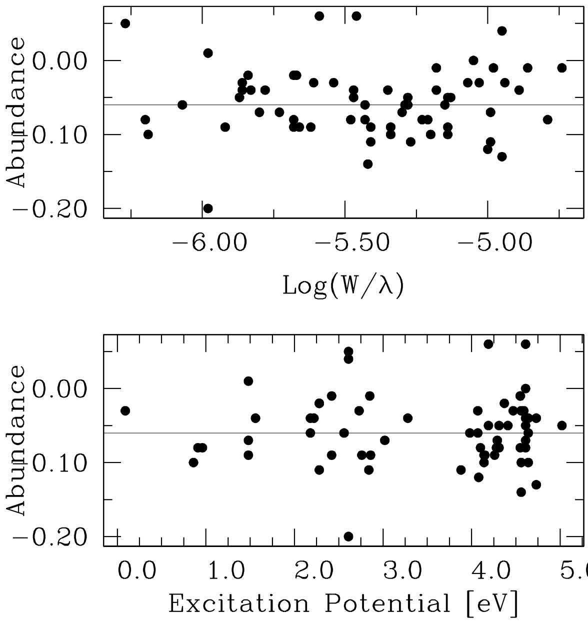

Fig. 2. Plots of abundance vs. excitation potential and abundance vs. $\log_{10}(W/\lambda)$ (logarithm of the reduced equivalent width) for HD 106252.

(2007) and Sozzetti et al. (2009) using essentially the same method are systematically lower (∼0.10 dex) than those derived by Ammler-von Eiff et al. (2009). The authors also mention differences in temperature (∼100 K) and gravity (∼0.15 dex) due to possible systematic differences between the works, and they note that the origin of the abundance discrepancies is usually unidentified.

We compare the parameters derived using FUNDPAR and those from the literature (Gonzalez 1997, 1998; Gonzalez et al. 1999; Santos et al. 2000; Gonzalez & Laws 2000; Gonzalez et al. 2001; Laws & Gonzalez 2001; Laws et al. 2003). We select these works in particular because they present the Fe equivalent widths: we use the same values with FUNDPAR. In the Table 4 we show the $T_{\rm eff}$, $\log g$, [FeI/H] and ξ obtained. Some stars in the table are listed twice (they are identified with a subscript) because we have different equivalent width sources in the literature. The sources of the equivalent widths are listed in the Table 4 as R1,...,R8.

We show in Figure 2 an example of plots of abundance vs. excitation potential and abundance vs. $\log_{10}(W/\lambda)$ (logarithm of the reduced equivalent width) for HD 106252. In Figure 3 we present the difference between FUNDPAR parameters and literature values (y axis, Δ=FUNDPAR-literature) vs. literature values (x axis). The empty point in Figure 3 corresponds to the star HD 38529, and shows that the slopes, metallicities and χ^2 values for this object should be taken with caution. The derived parameters of this star are based only on 3 FeII lines (and 24 FeI lines). In the literature, some values of $T_{\rm eff}$, $\log g$ and ξ have been rounded to within 50 K or 10 K, 0.05 dex and 0.1 km s^{-1}, respectively (see, for example, Gonzalez 1997, 1998; Gonzalez et al. 1999). There is a good agreement between FUNDPAR parameters and previous values from the literature, within the errors, which is expected since FUNDPAR uses a very similar method. However, Figure 3 shows that there is a dispersion in the values of the parameters (particularly $\log g$ and ξ) and probably a systematic trend for the metallicity (∼0.01 dex below literature values, see next discussion). The values of $\Delta T_{\rm eff}$ and $\Delta \log g$ also seem to slightly decrease with $T_{\rm eff}$ and $\log g$, respectively. The medians of the differences for the fundamental parameters compared to literature values are 24 K, 0.06 dex, 0.03 dex and 0.08 km s^{-1}, corresponding to $T_{\rm eff}$, $\log g$, [Fe/H] and ξ, respectively. The largest differences in the parameters amount to 118 K (16 Cyg B), 0.30 dex (HD 27442), 0.16 dex (16 Cyg B) and 0.31 km s^{-1} (47 Uma), corresponding to $T_{\rm eff}$, $\log g$, [Fe/H] and ξ, respectively.

Now we discuss the possible origin of the dispersions and probable trends observed in Figure 3. We tested FUNDPAR significantly modifying the values of the weights w_1,...,w_4 in the function χ^2 and verified that the difference in [Fe/H] compared with literature values and the dispersion of the other parameters change very slightly. Then the weights w_1,...,w_4 do not seem to be the cause. We use a method similar to that of the literature; however it is not totally identical. FUNDPAR uses Kurucz model atmospheres (Castelli & Kurucz 2003) different from those used in the literature (most of them date from before the creation of the ODFNEW models). The code uses model atmospheres derived by ATLAS with ODFNEW opacities and solar abundances from Grevesse & Sauval (1998) instead of Anders & Grevesse (1989). The new models present differences compared to older Kurucz models (Kurucz 1990), such as the solar abundances, the replacement of TiO and H_20 molecular lines, some HI quasi-molecular absorptions, etc. which are taken into account in the NEWODF opacities. Preliminary improvements are the $U-B$ and $u-b$ color indices for $T_{\rm eff} < 6750$ K, all color indices for cooler stars, and the better modeling for the upper layers of cool and giant stars (Castelli & Kurucz 2003). In this example, the model atmospheres are computed with con-

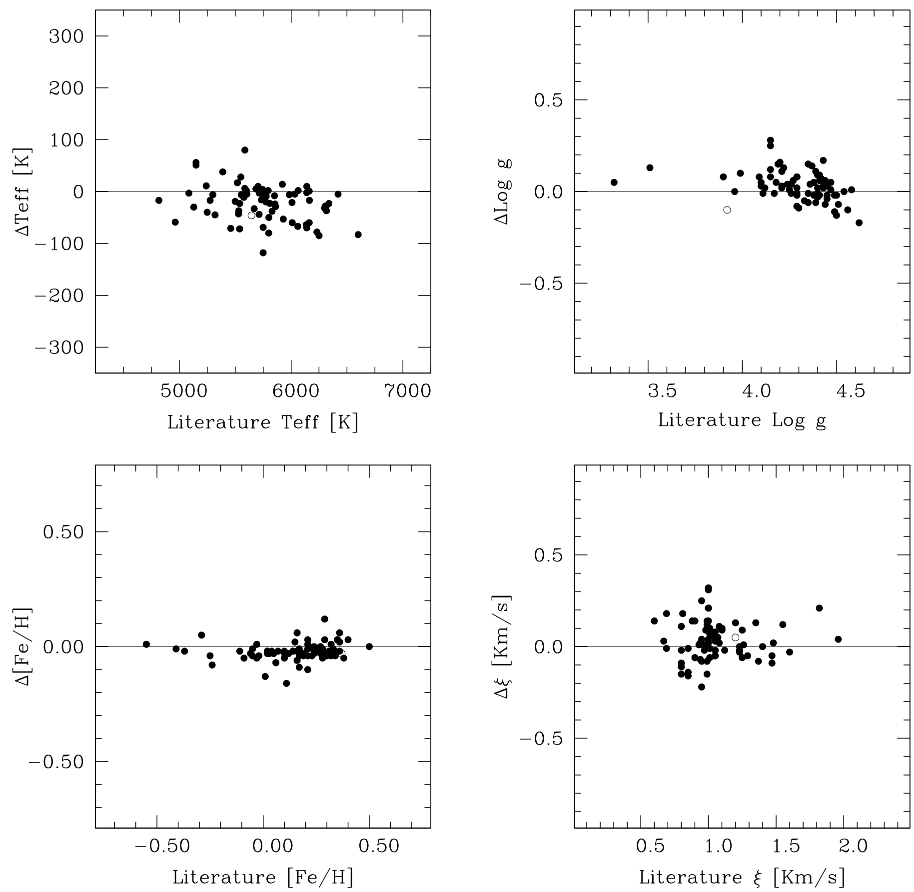

Fig. 3. Difference between FUNDPAR parameters and literature (y axis) vs. literature (x axis). The panels shows separately the effective temperature, gravity, metallicity and ξ. Filled and empty points correspond to solutions with $\chi^2 < 1$ and $\chi^2 > 1$, respectively.

vection (mixing-lenght parameter=1.25), overshooting (W=1) and damping in the Unsöld approximation, but multiplied by a factor as suggested by Blackwell, Lynas-Gray, & Smith (1995). The use of the fourth condition within the function χ^2 is (possibly) another difference from previous studies. Literature works surely take this into account, but it is not totally clear for us how they do so. Finally, we use the MOOG 2009 version[7] of the program instead of the 2002 version used in the literature, although we expect almost the same abundance values from both versions.

These differences, at least in part, produce the slightly dissimilar values showed in the Figure 3, which suggest that FUNDPAR probably uses a different metallicity scale than that of the literature. A complete comparison requires the exact knowledge of all involved details used in the literature calculations. Our intention is to clearly present all the asumptions used in FUNDPAR, in the model atmospheres and within the code.

In Figure 4 we show the histogram distributions of the uncertainties derived for $T_{\rm eff}$, $\log g$, [Fe/H] and ξ. The densely and slightly shaded histograms correspond to uncertaities derived following Gonzalez & Vanture (1998) and using the χ^2 function, respectively. Some distributions present a peak in a common uncertainty value, such as ∼0.05 dex in the [Fe/H] distribution and ∼30 K in the distribution of effective temperature. We see that the errors derived using both methods are comparable.

The metallicities presented in Table 4 correspond to a group of exoplanet host stars. The median of the group is 0.17 dex with a dispersion of 0.22 dex. In Figure 5 we present the histogram of the metallicity distribution. Then, as an example of the practical use of FUNDPAR, we verified the metal-rich nature of main sequence stars with low mass companions,

[7] `http://verdi.as.utexas.edu/moog.html`.

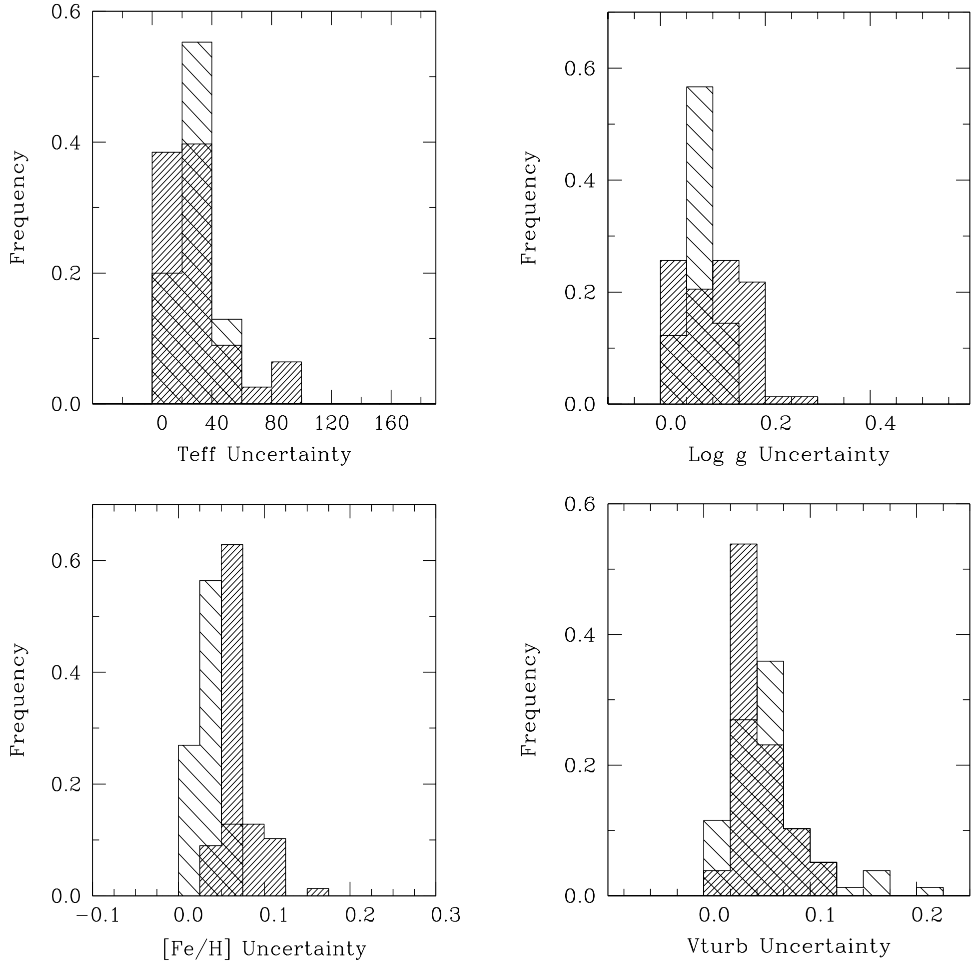

Fig. 4. Histogram distributions of the uncertainties in $T_{\rm eff}$, $\log g$, [Fe/H] and ξ derived with FUNDPAR. The densely and slightly shaded histograms correspond to uncertaities derived following Gonzalez & Vanture (1998) and using the χ^2 function, respectively.

a fact known from the literature (see, for example, Gonzalez 1997; Santos et al. 2000).

7. CONCLUDING REMARKS

We have implemented a Fortran algorithm available from the web that estimates fundamental parameters of solar type stars, requiring only the measurement of Fe equivalent widths. The final solution should verify the three conditions of the standard method: [FeI/H]=[FeII/H] (i.e., ionization equilibrium), independence of the metallicity from the excitation potential (i.e., excitation equilibrium) and from the equivalent widths. We also add another condition: the input metallicity used in the model atmosphere should be similar to the resulting metallicity from the equivalent widths. We taken into account these conditions in one variable called χ^2, adopting an expression which includes the weights w_1,...,w_4. FUNDPAR uses Kurucz model atmospheres with the NEWODF opacities (Castelli & Kurucz 2003), solar-scaled abundances from Grevesse & Sauval (1998) and the 2009 version of the MOOG program. Different details could be selected, such as the mixing-lenght parameter, the overshooting and the damping of the lines, for instance. We have planed a new version that includes the option of using the WIDTH9 program instead of MOOG.

The code includes the derivation of the uncertainty in the four parameters following the criteria of Gonzalez & Vanture (1998) and another uncertainty estimation using the χ^2 function. We verified the metal-rich nature of a group of exoplanet host stars. The parameters derived with FUNDPAR are in agreement with previous values in the literature.

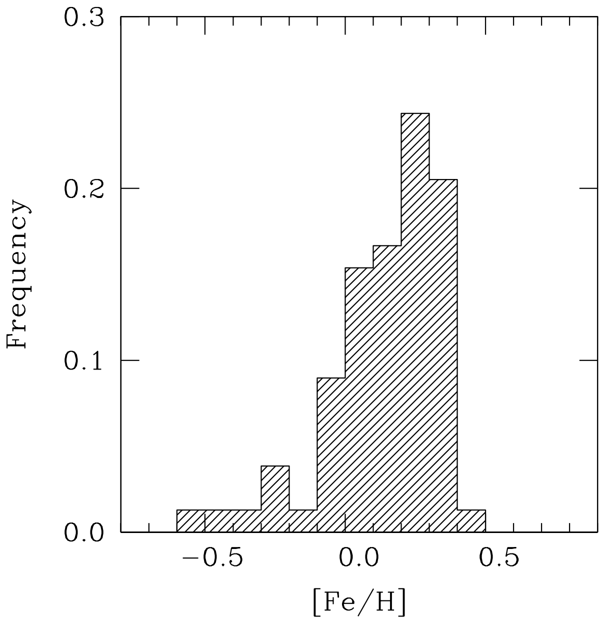

Fig. 5. Metallicity distribution of the sample stars derived by FUNDPAR.

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