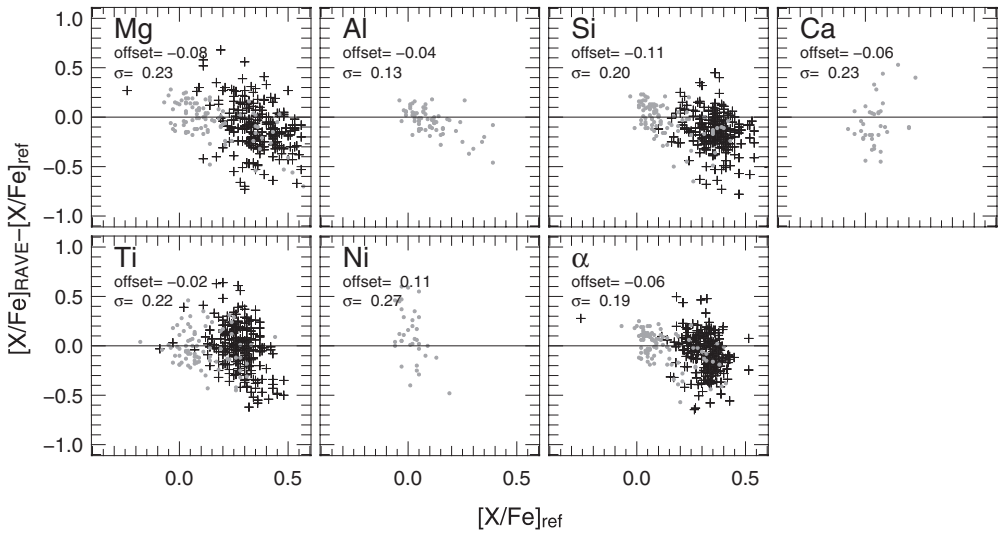

Figure 13. Same as Figure 11 but adopting $T_{\rm eff}$ and $\log g$ from the RAVE data (second test).

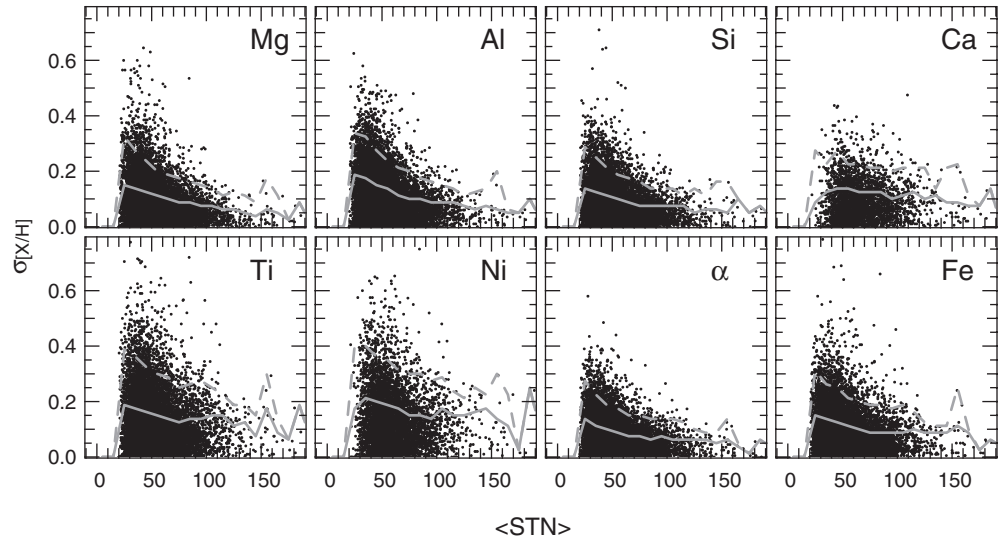

Figure 14. Expected internal errors of the chemical elemental abundances, estimated via standard deviations of the abundances from repeat observations. For a more robust statistic we used 30,821 spectra of 12,504 stars of the RAVE internal data release. The solid gray line represents the 1σ abundance error limit, i.e., 68% of the stars lie under the line for each STN bin, whereas the dashed gray line represents the 2σ limit. For this sample 9469 stars have two observations, 1286 have three, 1060 have four, 473 have five, 153 have six, 33 have seven, 11 have eight, 11 have nine, 4 have ten, and 4 have eleven observations.

Table 1
Mean and Standard Deviation of the Residuals between Measured and Expected Elemental Abundances Obtained by Using the High Resolution Stellar Parameters (Left) and the RAVE Parameters (Right) for 347 Standard Stars

Element Residuals	High Resolution Stellar Parameters				RAVE Stellar Parameters			
	Giants		Dwarfs		Giants		Dwarfs	
	Mean	σ (dex)	Mean	σ (dex)	Mean	σ (dex)	Mean	σ (dex)
[Mg/H]–[Mg/H]$_{\rm ex}$	−0.15	0.21	−0.08	0.14	−0.05	0.28	−0.06	0.15
[Al/H]–[Al/H]$_{\rm ex}$			−0.11	0.13			−0.11	0.15
[Si/H]–[Si/H]$_{\rm ex}$	−0.15	0.15	−0.04	0.09	0.11	0.21	−0.03	0.14
[Ca/H]–[Ca/H]$_{\rm ex}$			−0.13	0.20			−0.16	0.22
[Ti/H]–[Ti/H]$_{\rm ex}$	−0.14	0.17	−0.12	0.22	0.10	0.36	−0.03	0.30
[Fe/H]–[Fe/H]$_{\rm ex}$	−0.08	0.15	−0.06	0.15	0.07	0.30	0.04	0.31
[Ni/H]–[Ni/H]$_{\rm ex}$			−0.02	0.29			0.06	0.26
[α/H]–[α/H]$_{\rm ex}$	−0.10	0.15	−0.04	0.10	−0.02	0.21	−0.02	0.15

Notes. We computed the values for giants ($\log g < 3.5$) and dwarfs ($\log g \geqslant 3.5$) separately. The two groups are also representative of stars with $T_{\rm eff} < 5500$ K and intermediate STN (R10 stars), and stars with $T_{\rm eff} > 5500$ K and high STN (SG05 stars).

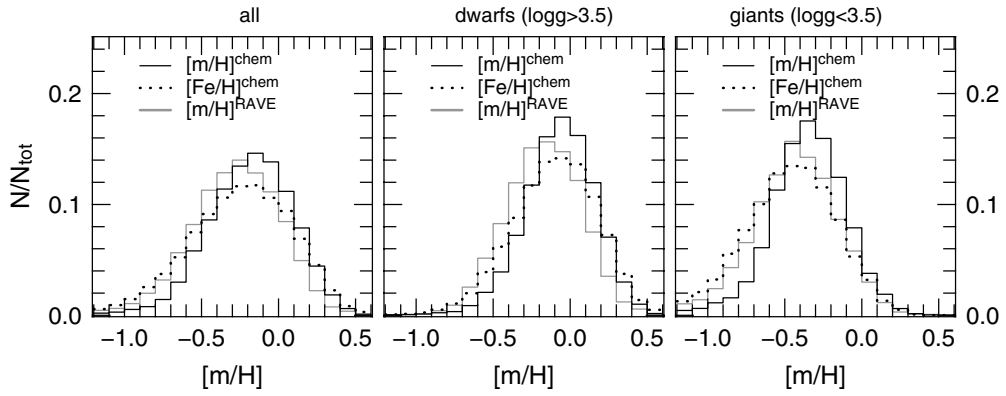

Figure 15. Comparison between $[m/H]^{chem}$ (black line) $[Fe/H]^{chem}$ (dotted line) and $[m/H]^{RAVE}$ (non-calibrated metallicity, gray line) distributions for the whole sample (37848 spectra, left panel), dwarf (middle panel), and giant stars (right panel).

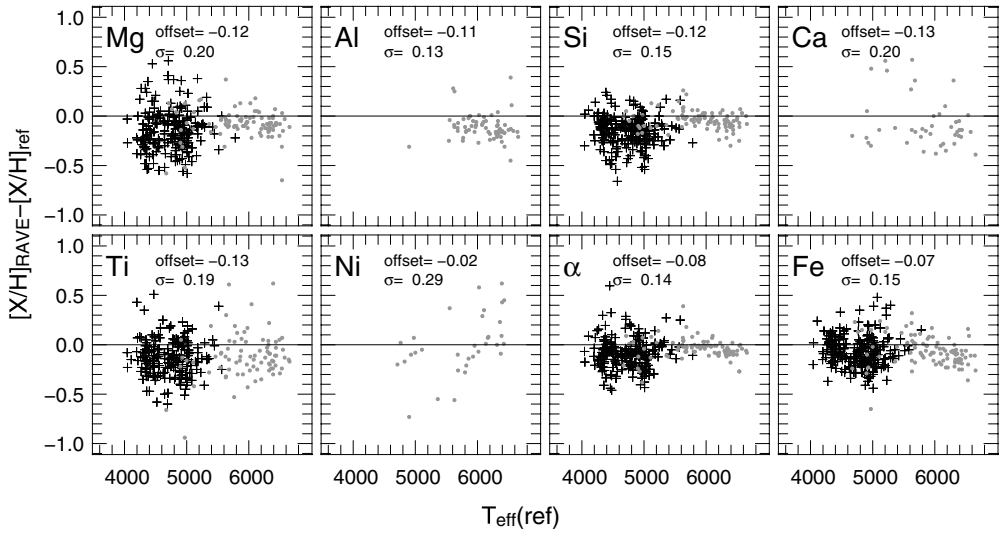

Figure 16. Residuals between measured and expected elemental abundances as a function of T_{eff}. For these measurements we adopted high-resolution stellar parameters. The symbols are as in Figure 10.

twice, 90 thrice, and 67 four times. Multiple observations are also useful to estimate the internal error by comparing the results obtained from different spectra of the same object. A fair comparison would require that the repeated observations of an object have the same S/N. Unfortunately, due to variable atmospheric conditions the spectra often have different S/N values. We therefore averaged the STNs of the spectra for each object and computed the corresponding standard deviations of the elemental abundances. In this way we could assess the magnitude of internal errors in our procedure as a function of STN. In Figure 14 we plot the results for 12,504 RAVE stars having multiple observations, where we use the RAVE internal data release as it has a substantially larger number of stars. For all the elements the 1σ confidence line (gray solid line) lies below 0.2 dex and hovers around ∼0.1 dex for STN > 80.

3.4. $[m/H]^{RAVE}$ versus $[m/H]^{chem}$: a Comparison

In Figure 15 we compare the distributions of $[m/H]^{RAVE}$, $[m/H]^{chem}$, and $[Fe/H]^{chem}$ for 37819 RAVE spectra with STN > 20. The metallicity $[m/H]^{chem}$ is inferred from the chemical elemental abundances with the equation given by Salaris et al. (1993)

$$[m/H]^{chem} = [Fe/H] + \log(0.638 \times 10^{[\alpha/Fe]} + 0.362), \quad (2)$$

where the α-enhancement is computed as

$$[\alpha/Fe] = \frac{[Mg/H] + [Si/H]}{2} - [Fe/H] \quad (3)$$

and the elemental abundances [Mg/H], [Si/H], and [Fe/H] come from the chemical pipeline.

$[m/H]^{RAVE}$ is ∼0.1 dex lower than $[m/H]^{chem}$, which is to be expected as the non-calibrated RAVE metallicity is underestimated by ∼0.15 dex with respect to the reference stars used in Siebert et al. (2011). The shape of the $[m/H]^{RAVE}$ distribution is fairly similar to the $[m/H]^{chem}$ distribution for dwarf stars but different for giants. Moreover, $[m/H]^{RAVE}$ seems to better match $[Fe/H]^{chem}$ than $[m/H]^{chem}$, particularly for giants. This could be due to α-enhancement: giant stars have a higher proportion of thick disk stars (α enhanced) than do dwarf stars, which are mostly thin disk (not α enhanced). Although used during the stellar parameters estimation process, the RAVE pipeline is unable to measure α-enhancement (Zwitter et al. 2008). Therefore, it is possible that particularly for α enhanced stars $[m/H]^{RAVE}$ better represents [Fe/H]. Apart from the discussed shift of 0.1 dex in metallicity, there seems to be fair agreement between the $[m/H]^{RAVE}$ and $[m/H]^{chem}$ distributions.

4. DISCUSSION

For each element, the accuracy of the abundance estimate depends on the number of lines that are strong enough to be clearly detected; to be measurable, the lines must be stronger than the noise. At the same time, the intensity of the lines depends on the stellar parameters and elemental abundances of the star. This means that for a fixed S/N, the accuracy of the elemental abundance is a function of the stellar parameters and of the abundance itself.

The interplay of these factors makes the accuracy of the abundance results difficult to estimate. At high S/N, the accuracy varies from element to element, depending on the number and intensity of the lines measured. For instance, Ti and Ni lines are measured better in stars with $T_{\rm eff}$ lower than ∼5000 K, whereas sulfur (not present in this data release) can be seen and measured only for temperatures higher than ∼4800 K. The RAVE line list has a few weak Ca I lines that can be measured only in stars with [m/H] > -0.5 dex.

Noise affects the EWs of the lines and so the model spectrum. As the pipeline varies the abundances of the individual elements, the larger the number the absorption lines of an element, the lower the abundance error due to the fitting, because the effects of noise are averaged over the lines. Thus, the abundance accuracy of elements with fewer lines is especially affected by noise. When the noise is particularly strong with respect to the intensity of the lines, i.e., low S/N, the minimization routine fits the noise and the resulting elemental abundance diverges. In such cases the pipeline rejects the measurement and renders a null value −9.99.

The situation get worse in the low S/N regime, because the pipeline measures even fewer lines, i.e., only those strong enough to be detected despite the noise. This decreases the number of measurable elements and increases the uncertainties. In Section 3.1, we tested the pipeline down to S/N = 20 to see if at such a low S/N the measurements are still trustworthy. The results suggest we can use such data, but with care. Noise generates selection effects: spectra having low [m/H] or high $T_{\rm eff}$ do not have lines strong enough to overcome the noise and they go through the pipeline unmeasured. A limited number of lines can also generate systematic errors because the abundance of an element depends on just a few lines (sometimes even only one) and thus becomes especially vulnerable to uncertainties in the oscillator strengths.

Nevertheless, the tests performed with synthetic spectra at S/N = 20 show that abundances of elements with strong lines like Fe, Al, and Si can still be measured. At such low S/N, errors as large as ∼0.2–0.3 dex are expected, but they do not show large systematic biases and the residuals are on average close to zero.

We conclude that elemental abundances may be trusted down to S/N = 40 for seven elements (details will follow in Section 5), whereas between S/N = 20 and 40 we can trust the abundance of [Fe/H] and (to be on the safe side) the abundance [α/H], when computed from the average of Mg and Si. Abundances for other elements for the low S/N stars should be considered indicative and used only for exploratory purposes until new comparison stars enable a proper validation of our results in this S/N regime.

4.1. Zero Point of the RAVE Elemental Abundance Scale

Our elemental abundance measurements are indirect measurements in the sense that they are inferred from the comparison between the intensity of lines seen in real spectra and their intensity predicted by stellar atmosphere models. Since the models are different for different stellar parameters, a question arises regarding whether all the models yield elemental abundances which refer to the same zero point, i.e., the origin of the internal elemental abundance scale. The same question concerns whether this zero point refers to the same zero point of the real spectra, i.e., between the internal and external scales.

The latter question has a prompt answer: we do not know the external scale, because real stellar atmospheres have never been directly probed and all elemental abundance measurements refer to models. Therefore, we can only check the consistency of the internal scale. This can be performed by comparing the measured elemental abundances of a sample of synthetic spectra at different stellar parameters, as done in Figure 6.

In this plot, at S/N = 100, the residuals between measured and expected elemental abundances are on average zero for any gravity and metallicity; the points align along a straight line with slope roughly equal to one. This means that the measured differences in elemental abundance at any metallicity regime are the same (constant offset), i.e., they refer to the same zero point. However, the offset from element to element may vary, showing that the offsets are due to the measurement process and not due to the metallicity of the atmosphere models.

On the other hand, there is a clear correlation between residuals and $T_{\rm eff}$: the higher the $T_{\rm eff}$, the higher the measured elemental abundance. This systematic may be due to continuum correction: cooler stars have spectra that are crowded with absorption lines and so the continuum appears lower than it is. Additionally, the varying behavior of the elements in Figure 6 can be explained by considering that their lines lie in different regions of the spectrum, i.e., on the wings of a Ca II line or in a region relatively free of lines. This can translate into systematic, wavelength-localized shifts of the estimated continuum as a function of $T_{\rm eff}$.

Although this systematic effect appears tractable and correctable, we did not apply any correction to the data because such a systematic is not visible on tests with real spectra. When the RAVE elemental abundances are compared with the expected elemental abundances of standard stars as function of $T_{\rm eff}$ no clear trend is visible (Figure 16), except that RAVE elemental abundances have a slight systematic bias to lower values. A reasonable explanation is that the elemental abundance measurements given by SG05 and R10 suffer from the same systematic error, due to uncertainties in estimating the correct continuum level in regions crowded with absorption lines or affected by the wings of strong, broad lines.

We conclude that the RAVE chemical pipeline can determine chemical elemental abundances with a systematic error that may be as large as ∼0.1 dex as a function of $T_{\rm eff}$. Since this systematic looks quite linear with $T_{\rm eff}$ (see Figures 9 and 16) to reduce this error to ±0.05 dex we suggest analyzing separately samples of stars with $T_{\rm eff} > 5500$ K (mostly dwarfs) from samples with $T_{\rm eff} < 5500$ K (mostly giants).

5. THE RAVE CHEMICAL CATALOG

We present the catalog of chemical elemental abundances for 36,561 RAVE stars, measured using 37,848 spectra.

5.1. Sample Selection

The spectra have been selected from the DR3 RAVE database using the following constraints.

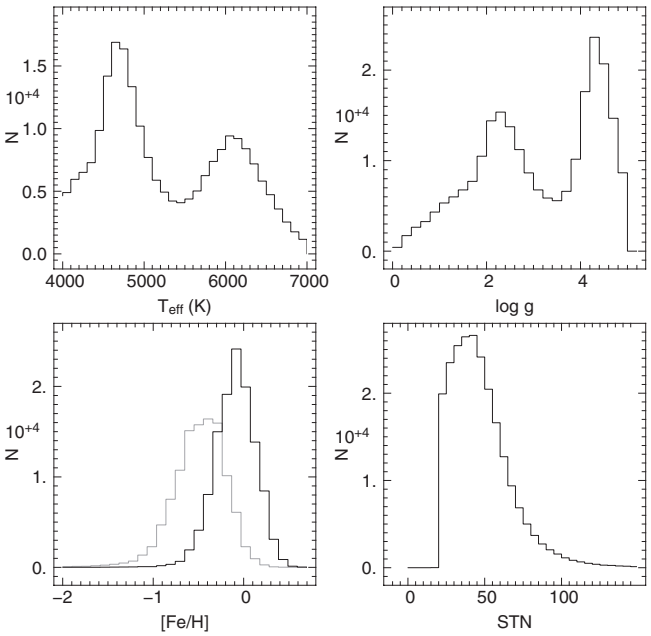

Figure 17. Distributions of stellar parameters $T_{\rm eff}$, log g, [Fe/H], and signal-to-noise ratio STN for 37848 spectra of the chemical catalog. In the bottom left panel, the [Fe/H] distribution is given separately for dwarfs (black line) and giants (gray line).

1. *Effective temperature 4000* $\leqslant$ $T_{\rm eff}(K)$ $\leqslant$ *7000*. This is the temperature range within which the RAVE line list has been calibrated. At lower temperature the spectra are characterized by molecular lines other than CN (CH, TiO, and other molecules), while at higher temperatures lines of ionized atoms appear, and both are not included in the line list.
2. *Signal-to-noise STN* $>$ *20*. For STN $<$ 20 the absorption lines are strongly affected by noise and the stellar parameters and chemical elemental abundances are not reliable.
3. *Rotational velocity* $V_{\rm rot}$ $<$ *50 km* s^{-1}. At higher rotational velocity the lines have an FWHM larger than that due to the spectral resolution (FWHM $\simeq$ 1.2 Å) and they cannot be precisely measured. Moreover, any spectra showing larger lines might be a double-lined spectrum, which also must be avoided.

Despite these selection criteria, some spectra exhibit emission or are affected by bad continuum normalization. For such spectra the stellar parameters and chemical elemental abundances are not reliable and it is advisable to reject them. Constraints on the parameters χ^2 and *frac* help identify these spectra. For statistical studies we suggest rejecting spectra with $\chi^2 > 2000$ and *frac* < 0.7, which removes 739 out of 37,848 spectra of the catalog.

5.2. Stellar Parameters

The distributions of the stellar parameters and STN values are presented in Figure 17. The quantities $T_{\rm eff}$ and log g are given by the RAVE data archive whereas STN and [Fe/H] are estimated by the chemical pipeline. The distributions in $T_{\rm eff}$ and log g show two peaks corresponding to giants at lower temperature and dwarfs, which are mostly at higher temperatures. The iron abundance distribution peaks at [Fe/H] $\simeq -0.1$ dex for dwarfs and [Fe/H] $\simeq -0.5$ dex for giants. The latter are in average more metal-poor because they lie further from the Galactic plane and have therefore a larger fraction of thick disk stars.[23]

5.3. Chemical Elemental Abundances: Selection Effects due to STN and Stellar Parameters

We encourage the user to pay particular attention to selection effects introduced by the stellar parameters and STN. Together they affect the total number of abundance estimations as well as their accuracy. Absorption lines can be undetectable because of the low [m/H] of the star, because the too-high (or too-low) $T_{\rm eff}$ does not populate enough of its electronic levels, or because the spectrum has a too-low STN. This is illustrated in Figures 18 and 19, where the number of spectra having [X/H] estimation diminishes with STN and [m/H]. In general, only metal-rich stars have elemental abundance estimations at any STN whereas metal-poor stars have estimations only if their spectra have high STN.

5.4. Accuracy and Reliability Element by Element

We now discuss and summarize the reliability of the chemical abundances for individual elements in light of the previous

[23] As RAVE is a magnitude limited survey, the intrinsically bright objects are on average at large distances.

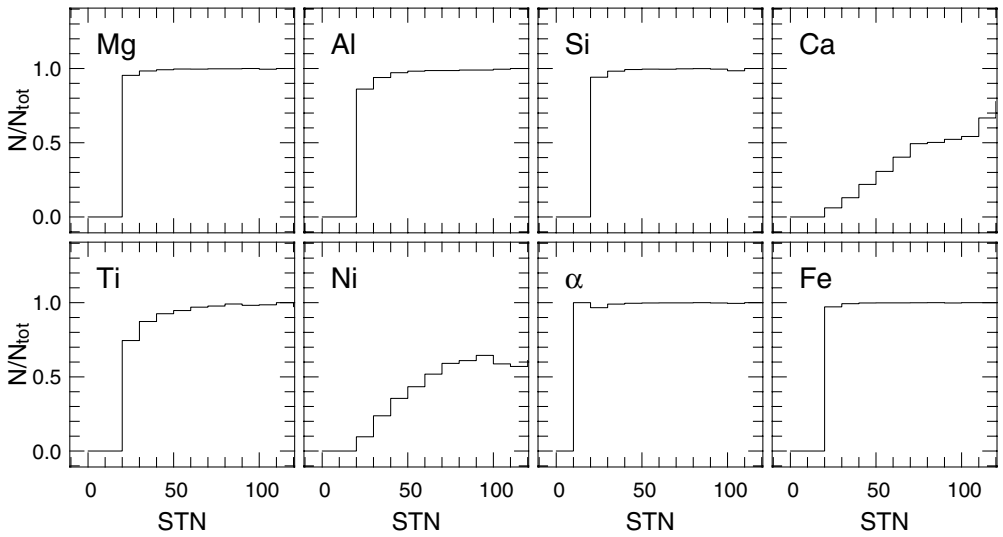

Figure 18. Fraction of spectra having elemental abundance measurements as a function of the STN. Every bin is normalized to the total number of observed spectra in the corresponding STN bin.

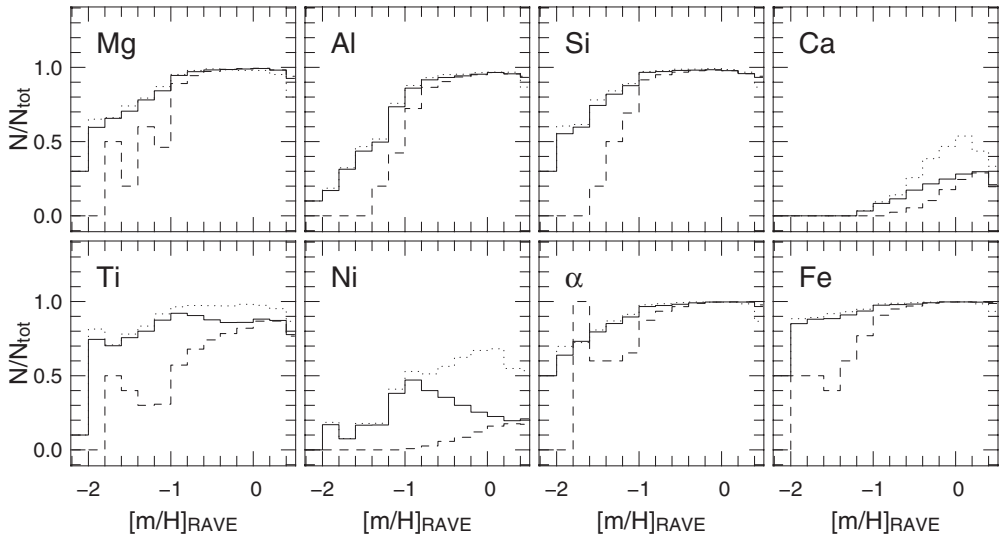

Figure 19. Fraction of spectra having elemental abundance measurements as a function of $[m/H]^{RAVE}$. Every bin is normalized to the total number of observed spectra in that $[m/H]^{RAVE}$ bin. The solid, dashed, and dotted lines represent the whole sample, dwarf stars only, and giants stars only, respectively.

Table 2
Catalog Description

Field Number	Name	Null Value	Description
1	RAVEID	...	RAVE target designation
2	Name	...	Target designation
3	Obsdate	...	Date of observation yyyymmdd
4	FieldName	...	Name of RAVE field
5	FiberNumber	...	Fiber number [1, 150]
6	[Mg/H]	−9.99	Mg abundance
7	*N*	...	Number of Mg lines measured
8	[Al/H]	−9.99	Al abundance
9	*N*	...	Number of Al lines measured
10	[Si/H]	−9.99	Si abundance
11	*N*	...	Number of Si lines measured
12	[Ca/H]	−9.99	Ca abundance
13	*N*	...	Number of Ca lines measured
14	[Ti/H]	−9.99	Ti abundance
15	*N*	...	Number of Ti lines measured
16	[Fe/H]	−9.99	Fe abundance
17	*N*	...	Number of Fe lines measured
18	[Ni/H]	−9.99	Ni abundance
19	*N*	...	Number of Ni lines measured
20	$T_{\rm eff}$	...	RAVE effective temperature
21	$\log g$	...	RAVE gravity
22	$[m/H]^{RAVE}$	...	RAVE metallicity
23	$[m/H]^{chem}$	...	Metallicity from the chemical pipeline
24	$[\alpha/Fe]^{chem}$	...	α-enhancement from the chemical pipeline
25	STN	...	Signal-to-noise ratio
26	frac	...	Fraction of spectrum matching the template well
27	Ntot	...	Total number of lines measured
28	χ^2	...	χ^2 between observed and template spectra

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

discussion. First, we make some general remarks about the measured elemental abundances and their errors.

1. The accuracy of the chemical abundances depends on several variables. In particular if $T_{\rm eff}$ is erroneously estimated, the abundances are affected to different degree for different elements. If there are systematics deviations in $T_{\rm eff}$ there will be systematic deviations in [X/H] as well.
2. In general [X/H] are underestimated, and the magnitude of the bias is a function of $T_{\rm eff}$: stars with $T_{\rm eff} < 5000$ K yield on average abundances that are ∼0.1 dex lower than stars with >5000 K, whose abundance errors average to zero. This effect increases the errors when stars with different $T_{\rm eff}$ are analyzed. On the other hand, *relative abundances [X/Fe] are nearly unaffected because the trend is similar for all elements*.

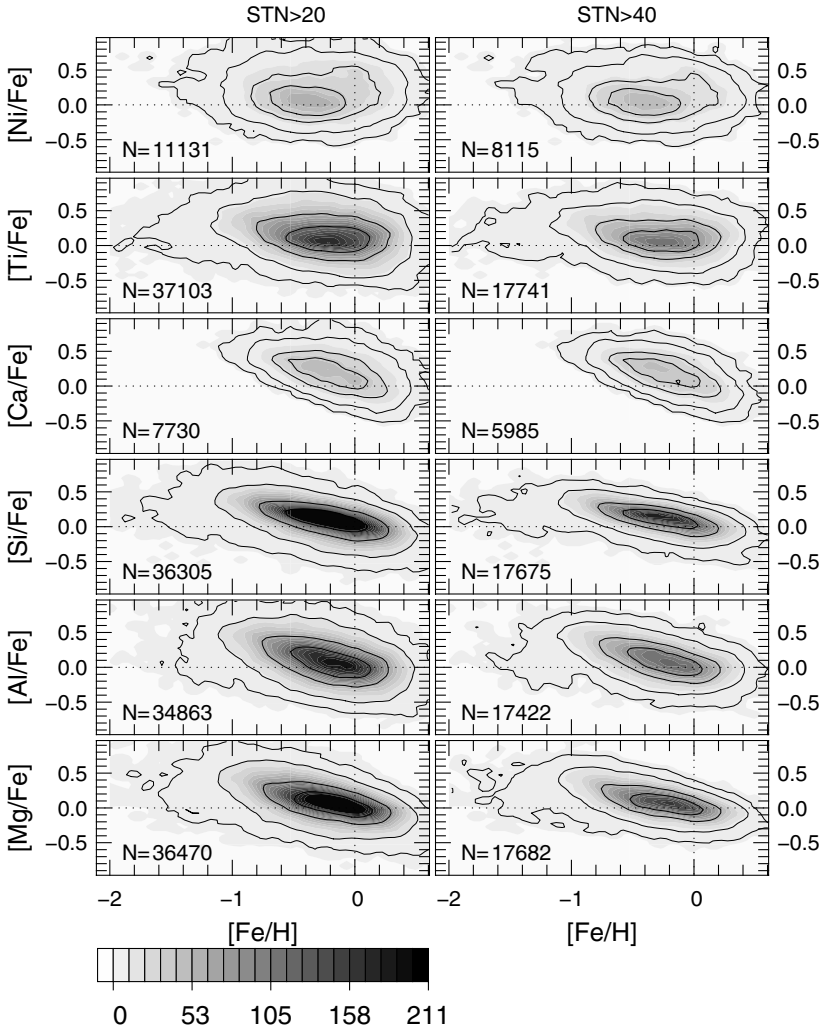

Figure 20. Abundances relative to iron for spectra with STN > 20 (left panels) and STN > 40 (right panels). The isocontours hold 34.0%, 68.0%, 95.0%, and 99.5% of the sample.

3. The errors given below refer to the expected errors for two intervals of STN at [m/H] ∼ 0.0 dex. As already discussed in the previous section, errors can increase for lower STN and lower [m/H].

Magnesium yields reliable results on synthetic and real spectra. At any $T_{\rm eff}$ we expect an abundance error $\sigma_{\rm Mg} \leqslant 0.15$ dex for STN $\geqslant 40$ and ∼0.25 dex for $20 \geqslant$ STN $\geqslant 40$.

Aluminum abundances are obtained from only two physically isolated lines (which are instrumentally blended at RAVE resolution). Despite the instrumental blending, the lines are strong and give accurate estimates in tests with synthetic and real spectra that shows no systematic offset. For STN $\geqslant 40$ we expect abundance errors $\sigma_{\rm Al} \leqslant 0.2$ dex and ∼0.3 dex for $20 \geqslant$ STN $\geqslant 40$.

Silicon is the most reliable element together with Fe. We expect an abundance error $\sigma_{\rm Si} \leqslant 0.15$ dex for STN $\geqslant 40$ and ∼0.20 dex for $20 \geqslant$ STN $\geqslant 40$.

Calcium abundances are obtained from only five weak Ca I lines. Ca I is better measured at higher metallicity and $T_{\rm eff} <$ 5000 K. Estimated errors are $\sigma_{\rm Ca}$ ∼0.25 dex for STN $\geqslant 40$ and ∼0.4 dex for $20 \geqslant$ STN $\geqslant 40$.

Titanium gives reliable abundances at high STN. At STN ∼ 40 its abundance is reliable for $T_{\rm eff} <$ 5000 K and underestimated for higher temperatures. The correlation with $T_{\rm eff}$ errors is particularly strong ($T_{\rm eff}$ underestimation generates [Ti/H] underestimation and vice versa) leading to larger errors. We expect an abundance error of $\sigma_{\rm Ti} \sim 0.2$ dex at STN $\geqslant 40$ and ∼ 0.3 dex for $20 \geqslant$ STN $\geqslant 40$. We recommend separately analyzing stars with $T_{\rm eff}$ lower and higher than 5000 K.

Iron is the most reliable element together with Si. It can be accurately measured on spectra with any $T_{\rm eff}$ in the range we consider. We expect an abundance error of $\sigma_{\rm Fe} \sim 0.1$ dex at STN $\geqslant 40$ and ∼0.2 dex at $20 \geqslant$ STN $\geqslant 40$.

Nickel has six weak lines in the RAVE wavelength range that are visible only at $T_{\rm eff} <$ 5000 K. In synthetic spectra with STN = 100 the pipeline yields errors comparable to those of other elements but biased to lower values by ∼0.2 dex. It is not measurable for [m/H] < -0.6 dex. Tests on real spectra are inconclusive because they were all performed for stars with $T_{\rm eff} >$ 5000 K. We expect uncertainties of $\sigma_{\rm Ni} \sim 0.2$ dex for STN $\geqslant 40$ and ∼0.3 dex for $20 \geqslant$ STN $\geqslant 40$. Because of the small number and the weakness of its lines, it is advisable to use Ni values with care.

The *overall metallicity* $[{\rm m/H}]^{\rm chem}$ is inferred from the chemical elemental abundances with Equation (2) (Salaris et al. 1993), with the abundances [Mg/H], [Si/H], and [Fe/H] delivered by the chemical pipeline. The metallicity $[{\rm m/H}]^{\rm chem}$ is reliable and we expect errors of $\sigma_{\rm [m/H]} \sim 0.1$ dex for STN $\geqslant 40$ and ∼0.2 dex for $20 \geqslant$ STN $\geqslant 40$.

The α-enhancement [α/Fe] has been computed as the average of [Mg/Fe] and [Si/Fe] (Equation (3)). In the range 20 ⩾ STN ⩾ 40 it is advisable to use it instead of the single α element values because it is more reliable. We estimate errors of $\sigma_\alpha \sim 0.1$ dex for STN ⩾ 40 and ∼0.2 dex for 20 ⩾ STN ⩾ 40.

5.5. The Data

The RAVE chemical catalog contains data for 37,848 spectra of 36,561 stars and it is provided as an ASCII table of 37,848 lines. It contains chemical abundances for the elements Mg, Al, Si, Ca, Ti, Fe, and Ni, RAVE stellar parameters, signal-to-noise STN, object name, and other parameters for quality checks as explained in Table 2. The distributions of the relative chemical abundances are shown in Figure 20. The catalog will be accessible online at http://www.rave-survey.org and via the Strasbourg Astronomical Data Center (CDS) service.

6. CONCLUSIONS

This first release of the RAVE chemical catalog reports the chemical abundances of seven elements (Mg, Al, Si, Ca, Ti, Fe, Ni) for 36,561 stars (from 37,848 spectra) selected from the DR3 data release. The chemical processing pipeline developed for the creation of the present catalog assures homogeneous elemental abundance measurements in addition to the RAVE pipeline that estimates the values of the stellar parameters and radial velocities.

The uncertainties in the estimated elemental abundances depend mostly on the signal-to-noise ratio (STN) of the spectra, on the values of the stellar parameters of the stars, and on the element considered. The expected errors in abundance can be as small as 0.1 dex at STN > 80 for the elements Fe and Si and up to ∼0.3 at 20 ⩾ STN ⩾ 40 for Ni.

On average we expect errors of ∼0.2 dex at STN ⩾ 40 for most of the elements. The relative abundances [X/Fe] are reliable with an underestimation of ∼−0.1 dex for [X/Fe] > +0.3.

We plan to increase the number of measured elements in future data releases. We believe that with further development of the chemical pipeline it should be possible to enrich the catalog with the abundances of at least two other elements (oxygen and sulfur).

The availability of chemical elemental abundances, together with the radial velocities of the stars (given in the RAVE DR3 data release) and their distances (Breddels et al. 2010; Zwitter et al. 2010; Burnett et al. 2011), makes RAVE a prime data set for Galactic archaeology investigations.

C.B. thanks M. Asplund, D. Yong, and F. Thévenin for the useful discussions he had with them.

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The RAVE Web site is at http://www.rave-survey.org.

APPENDIX A

CORRECTION OF THE ATOMIC OSCILLATOR STRENGTHS IN THE RAVE/*Gaia* WAVELENGTH REGION

In the following we outline how the pipeline treats oscillator strengths (gf, often expressed as a logarithm $\log gf$) in the wavelength range 8400–8800 Å. These are necessary in order to obtain trustworthy elemental abundance measurements in a wavelength region which is still poorly known. According to the VALD [1999] only 11 Fe lines have accurate gf-value laboratory measurements (Blackwell et al. 1986; Bard et al. 1991; Bard & Kock 1994), while the remaining hundreds of lines rely on theoretical and semi-empirical calculations (Kurucz 1995). Some of these values have proved imprecise, with errors as large as 1 dex for important lines belonging to Fe and Si (Bigot & Thévenin 2006). We have attempted to improve the oscillator strength values of 604 absorption lines using an inverse spectral analysis applied to spectra of the Sun and Arcturus.

A.1. Method

The RAVE line list consists of 604 absorption lines (excluding the H I and Ca II strong lines) identified by looking at the high S/N Sun and Arcturus spectra (Hinkle et al. 2000) and verified by cross checking the line identification of Moore et al. (1966) and Hinkle et al. (2000). Some previously unidentified lines have been added in order to match features that are clearly visible in spectra of the Sun and Arcturus.

The lines have been selected from Kurucz data (Kurucz 1995) and we have also adopted Kurucz's wavelengths and excitation potentials χ. Following Chen et al. (2000) we also adopted the enhancement factor E_γ for the Unsöld approximation because it is commonly accepted that the line broadening due to Van der Waals interaction obtained from Unsöld's approximation is too weak and needs to be corrected. For the CN molecule we used the dissociation energy $D = 7.75$ eV, as suggested by Sauval & Grevesse (1994).

We performed the inverse spectral analysis by synthesizing solar and Arcturus's spectra with MOOG (a standard LTE line analysis and synthesis code by Sneden 1973) and changing the $\log gf$s values until a good match with both observed spectra is reached. We show here that matching these two spectra (or more) allows us to improve the $\log gf$s of blended lines, which otherwise would be impossible to disentangle.

The EW of a measured absorption line is related to the $\log gf$-value through the curve of growth equation (see Gray 2005, formula 16.4)

$$\log \frac{\mathrm{EW}}{\lambda} = \log C + \log A + \log(gf \cdot \lambda) - \theta\chi - \log \kappa_\nu, \quad \text{(A1)}$$

where C and θ are functions[24] of the temperature T, and κ_ν is the opacity at the frequency ν. When all the atmosphere model

[24] C and θ are expressed as follows
$C = \text{constant} \cdot \frac{\pi e^2}{mc^2} \frac{N_j/N_E}{u(T)} N_\mathrm{H}$,
$\theta = 5040/T$,
where T is the temperature, N_j/N_E is the fraction of atoms of the jth stage of ionization with respect to the number of atoms of the element considered, N_H is the number of hydrogen atoms per unit volume, and $u(T)$ is the partition function.

parameters are fixed, the curve of growth equation can be written as a function, f, of $\log gf$ and elemental abundance A

$$\mathrm{EW} = f(\log gf, A). \quad \text{(A2)}$$

This allows us to disentangle two or more blended lines: let $\mathrm{EW}^x_{\mathrm{blend}}$ be the EW of a blended feature of the star x composed of n lines of m different elements ($n \geqslant m$) and having $\mathrm{EW}_1, \mathrm{EW}_2, ..., \mathrm{EW}_n$ unknown EWs. Then we can write the system of equations

$$\begin{aligned} \mathrm{EW}^1_{\mathrm{blend}} &= \sum^{n} f(\log gf_n, A_n) \quad \text{(A3)} \\ \mathrm{EW}^2_{\mathrm{blend}} &= \sum^{n} f(\log gf_n, A_n) \\ &\vdots \quad \vdots \\ \mathrm{EW}^N_{\mathrm{blend}} &= \sum^{n} f(\log gf_n, A_n), \end{aligned}$$

where A_n represents the abundance of the element the line belongs to.

Since the physical conditions and elemental abundance A of each stars are in general different, the values $\mathrm{EW}^x_{\mathrm{blend}}$ are different as well. The equation system A3 is solvable when the (N) number of equations is greater than the unknown $n+m$. The existence and uniqueness of the solution is assured even for lines where the weak-line approximation does not hold, because the first derivative of the curve of growth is always positive.

This means that it is always possible to determine the $\log gf$s of a blended feature and the elemental abundances by using a large enough number of spectra of different stars. In our case we have used two spectra: the Sun and Arcturus.

A.2. The Correction Routine

The following routine is valid when the stellar parameters and elemental abundances of both stars are known. We also consider later the case where elemental abundances are not known. To synthesize the solar spectrum we assumed an effective temperature $T_{\mathrm{eff}} = 5777$ K, gravity $\log g = 4.44$, microturbulence $V_t = 1.0\,\mathrm{km\,s^{-1}}$, and metallicity $[\mathrm{m/H}] = 0.00$. For Arcturus the atmospheric parameters are taken from Earle et al. (2005) ($T_{\mathrm{eff}} = 4340$ K, $\log g = 1.93$, $V_t = 1.87$ km s^{-1}, $[\mathrm{m/H}] = -0.55$ dex).

The synthetic spectra have been obtained assuming solar chemical abundances by Grevesse & Sauval (1998, hereafter GS98) and adopting the grid ATLAS9 model atmospheres of Castelli & Kurucz (2003). The $\log gf$s correction is performed using the following procedure.

1. Synthesize the solar and Arcturus spectra from our line list.
2. Select the first line of the list.
3. Integrate the absorbed flux of the observed and synthesized spectra over an interval spanning 0.4 Å around the center of the line (roughly 1 FWHM, which takes into account most of the absorbed flux) and calculate the normalized EW residual (NEWR), defined as follows

$$\mathrm{NEWR} = \frac{(F_{\mathrm{synt}} - F_{\mathrm{obs}})}{F_{\mathrm{obs}}}, \quad \text{(A4)}$$

where F_{synt} and F_{obs} are the flux of the synthetic and the observed spectrum, respectively. For the Sun and Arcturus we write ($\mathrm{NEWR_{Sun}}$) and ($\mathrm{NEWR_{Arc}}$).

Table 3
Arcturus's Elemental Abundances Compared with the Results by Luck & Heiter (2005, hereafter LH05), Thévenin (1998, hereafter T98), and Fulbright et al. (2007, hereafter F07)

Abundance	This Work	LH05	T98	F07
[O/H]	+0.17		−0.30	−0.10
[Mg/H]	−0.03	+0.02	−0.45	−0.10
[Al/H]	−0.27	−0.28	−0.40	−0.17
[Si/H]	−0.15	−0.14	−0.30	−0.15
[S/H]	−0.13			
[Ca/H]	−0.26	−0.56	−0.20	−0.28
[Ti/H]	−0.22	−0.39	−0.20	−0.20
[Cr/H]	−0.37	−0.55	−0.20	
[Fe/H]	−0.52	−0.55	−0.40	−0.54
[Co/H]	−0.17	−0.36	−0.20	
[Ni/H]	−0.45	−0.48	−0.35	
[Zr/H]	−1.00			

4. If $\mathrm{NEWR_{Sun}} < -0.05$ then add +0.01 to the $\log gf$, else if $\mathrm{NEWR_{Sun}} > 0.05$ then add −0.01 to the $\log gf$ (i.e., match the Sun first). Go to step 7.
5. If $|\mathrm{NEWR_{Sun}}| < 0.05$ and $\mathrm{NEWR_{Arc}} < -0.05$ then add −0.01 to the $\log gf$, else if $|\mathrm{NEWR_{Sun}}| < 0.05$ and $\mathrm{NEWR_{Arc}} > 0.05$ then add +0.01 to the $\log gf$ (e.g., if the Sun matches then try to match Arcturus). Go to step 7.
6. If $|\mathrm{NEWR_{Sun}}|$ and $|NEWR_{\mathrm{Arc}}|$ are both <0.05 then a valid $\log gf$ has been reached.
7. Select the next line from the line list and return to step 3.

The routine is iterated until no more improvement is seen. For about 10 lines a good match could not be reached. Several reasons may be behind this: bad continuum correction, lines located over the Ca II lines where the fit is inaccurate, misidentified lines, or unrecognized blends. For these lines, we did a visual check and manually corrected the $\log gf$ values. The correction is good enough to derive gf values that yield abundance errors per measured line smaller than 0.2 dex in average for both the Sun and Arcturus.

Since the abundance of Arcturus is not known for all elements, we decided to assume an initial abundance for all the elements ([X/H] = [m/H]) and find the right abundances with the following procedure.

1. Synthesize the Sun's and Arcturus's spectra.
2. Correct the $\log gf$-values by running the above correction routine until no more improvements are possible.
3. Check the distribution of the NEWRs for each element separately: if a positive/negative offset is present, decrease/increase its abundance.
4. Synthesize the solar and Arcturus's spectra with the new $\log gf$s and abundances.
5. Return to step 2.

This algorithm is repeated until there are no more improvements. The results of this procedure are the new $\log gf$s and Arcturus's chemical abundances (listed in Table 3).

A.2.1. Multiplets Treatment

In the RAVE/*Gaia* wavelength range there are features that belong to atomic multiplets. An interesting characteristic of these multiplets is that they share the same excitation potential χ and have small differences in wavelength. In this case, obtaining a proper $\log gf$ for the individual lines is problematic.

Table 4
Seven Lines Extracted from the RAVE Line List

Wavelength (Å)	Atomic Species	χ (eV)	$\log gf$	E_γ	Dissociation Energy (eV)
8643.306	26.0	4.913304	−2.470	1.40	0.00
8644.077	607.0	0.933782	−1.773	2.50	7.75
8646.050	607.0	1.324726	−1.540	2.50	7.75
8646.371	14.0	6.206423	−1.740	1.30	0.00
8647.175	607.0	0.877831	−1.872	2.50	7.75
8648.465	14.0	6.206423	0.100	1.30	0.00
8648.688	607.0	0.910915	−1.516	2.50	7.75

Notes. The whole table contains 604 lines with $\log gf$ correction, and the 3 Ca II and 8 H I lines which are not used for elemental abundance measurements (and did not undergo to $\log gf$ corrections). The atomic species 607.0 represent the CN molecule, following the MOOG format.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

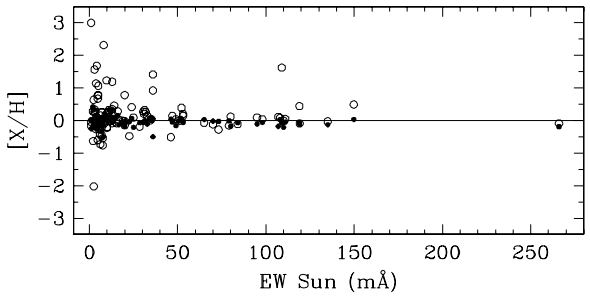

Figure 21. Solar elemental abundances obtained from 100 atomic lines for which EWs (x-axis) have been measured by hand from the solar spectrum. The open points represent the elemental abundances obtained by using the Kurucz gf-values, whereas the corrected gf-values are represented by the solid points. The respective dispersions are $\sigma = 0.63$ dex (open points) and $\sigma = 0.15$ dex (solid points).

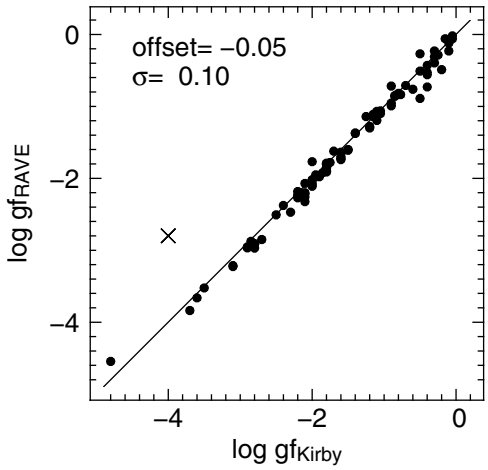

Figure 22. Comparison between corrected $\log gf$s by Kirby et al. 2008 (x-axis) and RAVE (y-axis). The statistics on the panel refers to points after the crossed outlier has been removed.

We work around this problem in the following way: consider the two Al I lines at $\lambda_1 = 8773.896$ Å and $\lambda_2 = 8773.897$ Å that share the same excitation potential $\chi = 4.021947$ eV. The two lines have unknown equivalent widths EW_1 and EW_2 but the sum

$$EW_{Tot} = EW_1 + EW_2, \tag{A5}$$

is measured and well known. We can write the curve of growth as

$$\frac{EW}{\lambda} = \frac{C \cdot A_{Al} \cdot (gf) \cdot \lambda}{10^{\theta\chi} \cdot \kappa_\nu}, \tag{A6}$$

where A_{Al} is the aluminum abundance and the other quantities are as in Equation (A1). Substituting Equation (A6) into Equation (A5) and adopting the approximation $\lambda_1 \simeq \lambda_2 = \lambda$ we obtain

$$\frac{EW_{Tot}}{\lambda} = \frac{EW_1 + EW_2}{\lambda} = \frac{C \cdot A_{Al} \cdot (gf_1 + gf_2) \cdot \lambda}{10^{\theta\chi} \cdot \kappa_\nu}. \tag{A7}$$

Using the logarithmic form, this equation then becomes

$$\log \frac{EW_{Tot}}{\lambda} = \log C + \log A + \log((gf_1 + gf_2) \cdot \lambda) - \theta\chi - \log \kappa_\nu, \tag{A8}$$

which suggests that an appropriate functional form for a "dummy" variable $\log gf_d$ would be $\log(gf_1 + gf_2)$. Even if this does not allow us to disentangle the two $\log gf$s, we can consider the multiplet as if it were one single line and correct the $\log gf_{fic}$; it will be a "dummy" value but it results in giving the correct abundance of Al. This correction has also been applied to three Mg I multiplets, centered at wavelengths 8717.814, 8736.020, and 8773.896 Å.

A.3. Tests

In order to test the accuracy of this procedure, we have measured by hand the EWs of 100 atomic lines in the solar spectrum. Figure 21 presents the difference in abundances obtained by using the Kurucz gf values (open points) and the corrected ones (solid points). Our correction reduced the standard deviations of the abundance residuals from $\sigma = 0.63$ dex to $\sigma = 0.15$ dex and their averages from +0.16 to −0.05.

We also compared our results to the $\log gf$ by Kirby et al. (2008), who corrected the gf values by applying a similar method, i.e., by synthesizing the solar and Arcturus's spectra and comparing the synthetic spectra with the observed ones. A comparison between our and their results is shown in Figure 22 for the 89 corrected lines in common: on average our $\log gf$ are lower by −0.05 dex. This is very likely due to different solar elemental abundances adopted: Kirby adopts the Anders & Grevesse (1989) abundances which are on average higher than Grevesse & Sauval (1998), which we adopt.

One more test involves comparing our results for Arcturus's elemental abundances with abundances quoted in the literature.

This is done in Table 3 where our elemental abundances are compared with those of Luck & Heiter (2005), Thévenin (1998, hereafter T98), and Fulbright et al. (2007, hereafter F07). From the consistency of these tests, we are confident that our computed $\log gf$ values are accurate and that our procedure yields robust and reliable elemental abundance estimates. In Table 4 we outline the final RAVE line list with the obtained $\log gf$.

APPENDIX B

MICROTURBULENCE

The polynomial function used to determine the microturbulence ξ is expressed as follows:

$$\xi_{\rm poly}({\rm km\ s^{-1}}) = \sum_{i,j=0,1,2,3}^{i+j\leqslant 3} a_{ij} T^i (\log g)^j, \qquad \text{(B1)}$$

where the coefficients a_{ij} are

$$\begin{aligned} a_{00} &= -10.3533 \qquad \text{(B2)}\\ a_{01} &= 2.59492\\ a_{02} &= 0.161863\\ a_{03} &= 0.176579\\ a_{10} &= 0.00509193\\ a_{11} &= -0.00157151\\ a_{12} &= -3.99782 \times 10^{-7}\\ a_{20} &= -0.000361822\\ a_{21} &= 3.82802 \times 10^{-7}\\ a_{30} &= -5.18845 \times 10^{-11}. \end{aligned}$$

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