A&A 497, 611–617 (2009)
DOI: 10.1051/0004-6361/200811508

Astronomy & Astrophysics

Both accurate and precise *gf*-values for Fe II lines*

J. Meléndez[1] and B. Barbuy[2]

[1] Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
e-mail: jorge@astro.up.pt
[2] Universidade de São Paulo, IAG, Rua do Matão 1226, Cidade Universitária, São Paulo 05508-900, Brazil

Received 11 December 2008 / Accepted 28 January 2009

ABSTRACT

We present a new set of oscillator strengths for 142 Fe II lines in the wavelength range 4000–8000 Å. Our gf-values are both accurate and precise, because each multiplet was globally normalized using laboratory data (accuracy), while the relative gf-values of individual lines within a given multiplet were obtained from theoretical calculations (precision). Our line list was tested with the Sun and high-resolution ($R \approx 10^5$), high-S/N (≈700–900) Keck+HIRES spectra of the metal-poor stars HD 148816 and HD 140283, for which line-to-line scatter (σ) in the iron abundances from Fe II lines as low as 0.03, 0.04, and 0.05 dex are found, respectively. For these three stars the standard error in the mean iron abundance from Fe II lines is negligible ($\sigma_{\rm mean} \leq 0.01$ dex). The mean solar iron abundance obtained using our gf-values and different model atmospheres is $A_{\rm Fe} = 7.45(\sigma = 0.02)$.

Key words. Sun: abundances – Sun: photosphere – stars: abundances – atomic data

1. Introduction

The iron abundance determined from Fe II lines is more reliable than that obtained from Fe I lines, as Fe II depends little on the details in the temperature structure of model atmospheres and it is almost immune to departures from LTE (e.g. Thévenin & Idiart 1999; Shchukina & Trujillo Bueno 2001; Gehren et al. 2001; Asplund 2005). Although some authors argue that small departures from LTE may be present for Fe II (e.g. Shchukina et al. 2005; Meléndez et al. 2006a), the effects are much less for Fe II than for Fe I. Thus, Fe II has recently been used as the preferred indicator for iron abundances in F-G-K type stars (e.g. Nissen et al. 2002, 2004, 2007; Meléndez & Barbuy 2002; Kraft & Ivans 2003; Asplund et al. 2006; Meléndez et al. 2006a; Ramirez et al. 2006), although some problems may be present for metal-rich late K dwarfs (e.g. Yong et al. 2004; Ramirez et al. 2007).

The robustness of Fe II is undermined by the uncertainty in their gf-values. As is well known in the literature, there is a lack of precise transition probabilities for Fe II lines, so that even the best available laboratory data introduce large uncertainties (at the level of 0.1 dex) in the determination of iron abundances (see e.g. Grevesse & Sauval 1999). New laboratory experiments and theoretical calculations (see Fuhr & Wiese 2006, and references therein) have not improved the situation, as will be shown in Sects. 3 and 4.

During the last few years we have critically evaluated each Fe II multiplet (as first described in Meléndez & Barbuy 2002), in order to improve the precision of the available data. Our whole line list has never been fully described or published, yet it is already being widely used in the literature (Meléndez & Barbuy 2002; Barbuy et al. 2006, 2007; Coelho et al. 2005; Meléndez et al. 2006a,b; Alves-Brito et al. 2005, 2006; Zoccali et al. 2004; Smiljanic et al. 2006, 2008; Allen & Barbuy 2006; Ramirez et al. 2006; Ramirez et al. 2007; Hekker & Meléndez 2007; Santos et al. 2009). In the present paper we present our improved oscillator strengths for Fe II lines, and we show that they are very precise and accurate and should be adopted until better laboratory and theoretical data are available.

2. Improved oscillator strengths

Even though the bulk of laboratory gf-values are probably correct on an absolute scale; i.e., they are probably accurate, the oscillator strengths have large uncertainties on a line-by-line basis, meaning that they are imprecise. On the other hand, theoretical calculations are not always correct on an absolute scale, but the theoretical relative line ratios within multiplets are reliable, except probably for lines with low f-values; as indicated by our tests using Fe I and Fe II lines, the relative agreement between theoretical and laboratory gf-values worsens for decreasing line strength (note that this behaviour has also been noted by other authors, e.g. Goldbach et al. 1989; Pickering et al. 2001), probably due to the difficulties in computing reliably gf-values for these lines (see e.g. Biémont et al. 1991; Raassen & Uylings 1998). In Meléndez & Barbuy (2002) we exploited the advantages of both laboratory and theoretical methods, adopting relative line ratios within a given multiplet from theoretical calculations, whereas the absolute transition probabilities for each multiplet were determined from laboratory measurements. For the present work we revised the gf-values of Fe II lines, using new laboratory and theoretical data.

We have adopted theoretical gf-values by Biémont et al. (1991), Raassen & Uylings (1998), and recent calculations by Kurucz[1]. Those data were calibrated with the following experimental data: lifetimes of upper levels from

* Based in part on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

[1] As published online in October 2003 and August 2008 at http://kurucz.harvard.edu

Article published by EDP Sciences

Schnabel et al. (2004), Schnabel et al. (1999), Schnabel & Kock (2001), Guo et al. (1992), Hannaford et al. (1992), and Biémont et al. (1991), and branching fractions by Heise & Kock (1990), Pauls et al. (1990), and Kroll & Kock (1987). The (absorption) oscillator strength $f_{\rm lu}$ is related to the branching fraction ($BF_{\rm lu}$) and the lifetime ($\tau_{\rm u}$) by (e.g. Hannaford 1994):

$$f_{\rm lu} = 1.499 \times 10^{-7} (g_{\rm u}/g_{\rm l})(BF_{\rm lu}/\tau_{\rm u}[ns])\lambda^2\ [\text{Å}] \quad (1)$$

where $\tau_{\rm u}$ is given in ns and the wavelength of the transition λ in Å; l and u represent the lower and upper levels, respectively; $g_{\rm l}$ and $g_{\rm u}$ are the statistical weights of the lower and upper levels, respectively, which depend on the total angular momentum of the level, i.e. on the quantum number J:

$$g = 2J + 1.$$

Since the ratio BF/τ is equivalent to the transition probability A ($= BF/\tau$), the oscillator strength can also be obtained from

$$f_{\rm lu} = 1.499 \times 10^{-7} (g_{\rm u}/g_{\rm l})A_{\rm ul}[10^9\ {\rm s}^{-1}]\lambda^2[\text{Å}] \quad (2)$$

where $A_{\rm ul}$ is given in $10^9\ {\rm s}^{-1}$ and λ in Å.

When no laboratory measurement for any line of a multiplet was available, the relative oscillator strengths were derived from theoretical calculations, but the absolute gf-values of the multiplet were obtained from an inverse analysis based on the National Solar Observatory FTS solar flux spectrum by Hinkle et al. (2000), which is essentially the same spectrum as was previously published by Kurucz et al. (1984) but corrected for telluric absorption. The solar analysis was performed with the codes ABON 2002 (Spite 1967) and MOOG 2002 (Sneden 1973), using a spatially and temporally averaged 3D solar model atmosphere (hereafter ⟨3D⟩; Asplund et al. 2004) and adopting a solar abundance obtained with the ⟨3D⟩ model and the previously determined laboratory gf-values of the Fe II lines and with interaction constants C_6 computed from broadening cross-sections σ calculated by Barklem & Aspelund-Johansson (2005), using the following relation (derived from Gray (2005), as described in Coelho et al. 2005):

$$C_6[{\rm cm}^6\ {\rm s}^{-1}] = 6.46 \times 10^{-34} (\sigma[{\rm a.u.}]/63.65)^{5/2} \quad (3)$$

where the cross-section σ is given in atomic units and the interaction constant C_6 in ${\rm cm}^6\ {\rm s}^{-1}$.

When the relative line ratios predicted by the theoretical calculations fail to reproduce the observed solar line ratios within a given multiplet, we preferred to adopt gf-values based entirely on laboratory measurements or to make slight corrections (usually no larger than 0.1 dex) to reproduce the solar spectrum better. This was mainly the case for weak lines, because their theoretical line ratios may be incorrect.

The complete line list of 142 Fe II lines is given in Table 1, where gf-values based on laboratory or solar measurements are labelled L or S, respectively. The C_6 constants computed from Eq. (3) are also given in the Table 1. For five lines (given between parenthesis in Table 1) cross-sections were not explicitly computed by Barklem & Aspelund-Johansson (2005). In those cases we obtained C_6 from other lines of the same multiplet.

The procedure adopted here is very time-consuming, as each multiplet is evaluated individually, but the results are worthwhile and will significantly improve the precision of iron abundances obtained from Fe II lines, as shown in the next sections.

3. The solar iron abundance

As discussed by Grevesse & Sauval (1999), it is very disappointing that accurate transition probabilities are known for only a very few Fe II lines, making the iron abundance obtained from Fe II very uncertain, with a line-to-line scatter as high as 0.1 dex.

To test that our gf-values reduce the scatter in the solar iron abundance, we rescaled a few representative solar iron abundance determinations from the literature using a total of 43 different Fe II lines (Biémont et al. 1991; Hannaford et al. 1992; Schnabel et al. 1999; Asplund et al. 2000). Since the scatter in the abundances is very high, we have used the median instead of the average here (and in the next section). The results are shown in Table 2 and Figs. 1–4. We succeed in all cases to lower the uncertainties significantly, with an improvement as high as almost a factor of 3 for the Hannaford et al. (1992) data (Fig. 1), for which the σ was reduced from 0.084 dex to only 0.030 dex. The −0.05 dex correction proposed by Biémont et al. to their theoretical gf-values may not be necessary, otherwise their mean solar iron abundance would be $A_{\rm Fe} = 7.54$.

The gf-values given by Schnabel et al. (2004) for lines used in the solar iron abundance determination are very similar to those given in Schnabel et al. (1999), and indeed the result given by Schnabel et al. (2004) is the same (both in the mean value and line-to-line scatter) as in Schnabel et al. (1999), $A_{\rm Fe} = 7.42$ ($\sigma = 0.09$); therefore, the revised values given by Schnabel et al. (2004) do not improve the precision of their older transition probabilities. The gf-values given in the critical compilation of Fuhr & Wiese (2006) in the optical region are mainly based on the laboratory results of Schnabel et al. (2004), which are not very precise as discussed above, and the (uncorrected) theoretical results of Raassen & Uylings (1998), which are not very accurate. Indeed, the solar iron abundance obtained by Raassen & Uylings (1998) is 7.59, much higher than the meteoritic iron abundance (7.45 ± 0.03; Asplund 2005).

Given the importance of the solar iron abundance as a standard reference in astronomy, we have computed its abundance using our gf-values for the 15 lines analysed in Hannaford et al. (1992). The (centre of the disk) equivalent widths adopted here are shown in Table 3; they are the average of the measurements presented in Holweger et al. (1990), Biémont et al. (1991), Hannaford et al. (1992), and Grevesse & Sauval (1999). The calculations were performed with MOOG 2002 using six model atmospheres: the Holweger & Müller (1974) model atmosphere, Kurucz overshooting (Castelli et al. 1997) and the latest no-overshooting (Castelli & Kurucz 2004) models, the MARCS 1997 (Asplund et al. 1997) and MARCS 2008 (Gustafsson et al. 2008) models, and the ⟨3D⟩ solar model (Asplund et al. 2004). The results are shown in Table 4, where rescaled results based on a three-dimensional hydrodynamical model of the solar atmosphere (Asplund et al. 2000) are also presented. The individual iron abundances for each model atmosphere have a very low line-to-line scatter ($\sigma < 0.03$ dex) and the standard error ($\sigma_{\rm mean} = \sigma/\sqrt{n}$) for the mean value is negligible ($\sigma_{\rm mean} < 0.01$ dex). The different models give about the same result, $A_{\rm Fe} \approx 7.45(\sigma = 0.02)$, but values as low as 7.42–7.43 (e.g. see Fig. 5 for the MARCS 2008 model), i.e., slightly lower than the meteoritic iron abundance, are not unlikely, although alternatively it may imply that the transformation between the solar and meteoritic abundance scales may be slightly in error. Interestingly, a recent work by Meléndez et al. (2009), in a comparison of the Sun with solar twins, shows that the solar photosphere may be slightly depleted in refractory elements (including iron).

Table 1. Fe II line list.

λ (Å)	$\chi_{\rm exc}$ (eV)	log gf	C_6	λ (Å)	$\chi_{\rm exc}$ (eV)	log gf	C_6	λ (Å)	$\chi_{\rm exc}$ (eV)	log gf	C_6
4087.284	2.5828	-4.57^{L}	(0.857E-32)	4855.554	2.7045	-4.46^{S}	0.787E-32	6147.741	3.8887	-2.69^{S}	0.943E-32
4122.668	2.5828	-3.26^{L}	0.869E-32	4871.277	2.7045	-4.25^{S}	0.787E-32	6149.258	3.8894	-2.69^{S}	0.943E-32
4128.748	2.5828	-3.63^{L}	0.956E-32	4893.820	2.8283	-4.21^{S}	0.787E-32	6150.098	3.2215	-4.73^{S}	0.787E-32
4173.461	2.5828	-2.65^{L}	0.943E-32	4923.927	2.8912	-1.26^{L}	0.810E-32	6179.384	5.5687	-2.62^{S}	0.155E-31
4178.862	2.5828	-2.51^{L}	0.857E-32	4924.921	2.8443	-4.90^{S}	0.787E-32	6184.929	5.5709	-3.72^{S}	0.787E-32
4233.172	2.5828	-1.97^{L}	0.943E-32	4991.126	2.7786	-4.55^{S}	0.787E-32	6233.534	5.4845	-2.51^{S}	0.155E-31
4258.154	2.7045	-3.33^{L}	0.869E-32	4993.358	2.8066	-3.62^{S}	0.775E-32	6238.392	3.8887	-2.60^{L}	0.943E-32
4273.326	2.7045	-3.38^{L}	0.956E-32	5000.743	2.7786	-4.61^{S}	0.787E-32	6239.953	3.8894	-3.41^{S}	0.943E-32
4278.159	2.6921	-3.73^{L}	(0.845E-32)	5018.440	2.8912	-1.10^{L}	0.798E-32	6247.350	6.2090	-1.98^{S}	0.881E-32
4296.572	2.7045	-2.92^{L}	0.869E-32	5036.920	2.8283	-4.67^{S}	0.775E-32	6247.557	3.8918	-2.30^{S}	0.943E-32
4303.176	2.7045	-2.56^{L}	0.943E-32	5100.664	2.8066	-4.17^{S}	0.787E-32	6248.898	5.5110	-2.67^{S}	0.159E-31
4351.769	2.7045	-2.25^{L}	0.943E-32	5120.352	2.8283	-4.24^{S}	0.787E-32	6317.983	5.5110	-1.96^{S}	0.159E-31
4369.411	2.7786	-3.65^{L}	0.869E-32	5132.669	2.8066	-4.08^{S}	0.775E-32	6331.954	6.2173	-1.88^{S}	0.881E-32
4384.319	2.6570	-3.44^{L}	0.845E-32	5136.802	2.8443	-4.43^{S}	0.787E-32	6369.462	2.8912	-4.11^{L}	0.742E-32
4385.387	2.7786	-2.66^{L}	0.943E-32	5146.127	2.8283	-3.91^{S}	0.787E-32	6371.125	5.5491	-3.13^{S}	0.153E-31
4413.601	2.6759	-3.79^{L}	0.845E-32	5150.941	2.8557	-4.48^{S}	0.787E-32	6383.722	5.5526	-2.24^{S}	0.159E-31
4416.830	2.7786	-2.65^{L}	0.943E-32	5154.409	2.8443	-4.13^{S}	0.787E-32	6385.451	5.5526	-2.59^{S}	0.159E-31
4472.929	2.8443	-3.36^{L}	(0.869E-32)	5161.184	2.8557	-4.47^{S}	0.787E-32	6416.919	3.8918	-2.64^{S}	0.930E-32
4489.183	2.8283	-2.96^{L}	0.869E-32	5169.033	2.8912	-1.00^{L}	0.798E-32	6432.680	2.8912	-3.57^{L}	0.742E-32
4491.405	2.8557	-2.71^{L}	0.869E-32	5171.640	2.8066	-4.54^{S}	0.775E-32	6433.814	6.2191	-2.37^{S}	0.881E-32
4508.288	2.8557	-2.44^{L}	0.956E-32	5197.577	3.2306	-2.22^{L}	0.869E-32	6442.955	5.5491	-2.44^{S}	0.155E-31
4515.339	2.8443	-2.60^{L}	0.869E-32	5234.625	3.2215	-2.18^{L}	0.869E-32	6446.410	6.2225	-1.97^{S}	0.881E-32
4520.224	2.8068	-2.65^{L}	0.857E-32	5238.624	2.8912	-5.11^{S}	(0.798E-32)	6455.837	5.5526	-2.92^{S}	0.159E-31
4522.634	2.8443	-2.25^{L}	0.943E-32	5256.938	2.8912	-4.06^{S}	0.798E-32	6456.383	3.9036	-2.05^{S}	0.930E-32
4534.168	2.8557	-3.28^{L}	0.869E-32	5264.812	3.2304	-3.13^{L}	0.943E-32	6482.204	6.2191	-1.78^{S}	0.881E-32
4541.524	2.8557	-2.98^{L}	0.943E-32	5276.002	3.1996	-2.01^{L}	0.857E-32	6491.246	5.5851	-2.76^{S}	0.160E-31
4549.192	5.9113	-1.62^{L}	0.142E-31	5284.109	2.8912	-3.11^{S}	0.798E-32	6493.035	5.5851	-2.55^{S}	0.160E-31
4549.474	2.8283	-2.09^{L}	0.943E-32	5316.615	3.1529	-1.87^{L}	0.845E-32	6506.333	5.5895	-2.68^{S}	0.159E-31
4555.893	2.8283	-2.40^{L}	0.857E-32	5316.784	3.2215	-2.74^{L}	0.943E-32	6508.129	5.5895	-3.45^{S}	0.159E-31
4576.340	2.8443	-2.95^{L}	0.943E-32	5325.553	3.2215	-3.16^{L}	0.857E-32	6516.080	2.8912	-3.31^{L}	0.742E-32
4582.835	2.8443	-3.18^{L}	0.857E-32	5337.732	3.2304	-3.72^{L}	0.943E-32	6517.018	5.5851	-2.73^{S}	0.159E-31
4583.837	2.8068	-1.93^{L}	0.930E-32	5362.869	3.1996	-2.57^{L}	0.930E-32	6562.200	5.6052	-2.83^{S}	0.160E-31
4601.378	2.8912	-4.48^{L}	0.918E-32	5414.073	3.2215	-3.58^{L}	0.930E-32	6586.699	5.6052	-2.74^{S}	0.160E-31
4620.521	2.8283	-3.21^{L}	0.930E-32	5425.257	3.1996	-3.22^{L}	0.845E-32	6598.301	5.6156	-3.05^{S}	0.157E-31
4625.893	5.9560	-2.35^{L}	0.143E-31	5432.967	3.2675	-3.38^{S}	0.857E-32	7222.394	3.8889	-3.26^{L}	0.956E-32
4629.339	2.8068	-2.34^{L}	0.845E-32	5525.125	3.2676	-3.97^{L}	0.918E-32	7224.487	3.8891	-3.20^{L}	0.956E-32
4635.316	5.9560	-1.42^{L}	0.143E-31	5534.847	3.2449	-2.75^{S}	0.845E-32	7301.560	3.8916	-3.63^{S}	0.857E-32
4648.944	2.5828	-4.58^{S}	0.775E-32	5591.368	3.2675	-4.44^{S}	0.845E-32	7308.073	3.8889	-3.03^{L}	0.943E-32
4656.981	2.8912	-3.60^{L}	0.918E-32	5627.497	3.3866	-4.10^{L}	0.869E-32	7310.216	3.8891	-3.37^{L}	0.943E-32
4666.758	2.8283	-3.28^{L}	0.845E-32	5657.935	3.4247	-4.03^{L}	0.869E-32	7320.654	3.8918	-3.23^{L}	0.943E-32
4670.182	2.5828	-4.09^{S}	0.775E-32	5725.963	3.4247	-4.76^{L}	0.869E-32	7449.335	3.8889	-3.27^{L}	0.943E-32
4720.149	3.1974	-4.48^{S}	0.930E-32	5732.724	3.3866	-4.60^{L}	0.857E-32	7462.407	3.8918	-2.74^{L}	0.943E-32
4731.453	2.8912	-3.10^{L}	0.905E-32	5813.677	5.5706	-2.51^{L}	0.798E-32	7479.693	3.8916	-3.61^{S}	0.857E-32
4825.736	2.6350	-4.87^{S}	0.775E-32	5991.376	3.1529	-3.54^{S}	0.775E-32	7515.832	3.9036	-3.39^{L}	0.943E-32
4831.126	3.3394	-4.89^{S}	0.943E-32	6084.111	3.1996	-3.79^{S}	0.787E-32	7655.488	3.8918	-3.56^{L}	0.930E-32
4833.197	2.6572	-4.64^{S}	0.775E-32	6113.322	3.2215	-4.14^{S}	0.787E-32	7711.724	3.9034	-2.50^{L}	0.930E-32
4833.865	2.8443	-5.11^{S}	(0.787E-32)	6116.057	3.2306	-4.67^{S}	0.787E-32				
4839.998	2.6757	-4.75^{S}	0.787E-32	6129.703	3.1996	-4.64^{S}	0.775E-32				

Note.- Lines from multiplets normalized using laboratory data are labelled L, and the Sun S. The broadening constants C_6 are based on cross-section calculations by Barklem & Aspelund-Johansson (2005).

4. The metal-poor stars HD 140283 and HD 148816

As shown in Sect. 3, our gf-values are adequate for solar metallicity stars. However, many Fe II lines that are useful in metal-poor stars are blended or too strong in the Sun. Therefore, we performed further tests of our line list using the metal-poor stars HD 148816 and HD 140283, which have roughly solar effective temperature, but an iron abundance about 5 times and 200 times lower than in the Sun, respectively.

The sample stars were observed with HIRES (Vogt et al. 1994) at the Keck I telescope in June 2005, i.e., after the HIRES upgrade (August 2004) which improved the efficiency, spectral coverage and spectral resolution of HIRES. A resolving power of $R \approx 10^5$ was achieved using a 0.4″-wide slit. The combined spectra of HD 140283 have S/N of about 800 and 900 per pixel at 5000 and 6500 Å, respectively, while in the case of HD 148816 we achieved S/N of ≈700 and 800 in the same regions.

The superb quality of the spectra guarantees a very stringent test of our line list, as the photon noise will not significantly influence the line-to-line scatter in the iron abundance. A full description of the data for these and other metal-poor stars

Table 2. Corrected literature solar iron abundances from Fe II lines using our line list.

Model	gf-value	A_{Fe}(literature)	# lines	Reference	A_{Fe}(corrected)
HM	laboratory	7.480 (σ = 0.084)	15	Hannaford et al. (1992) (H92)	7.470 (σ = 0.030)
HM	laboratory	7.420 (σ = 0.088)	13	Schnabel et al. (1999) (S99)	7.450 (σ = 0.054)
3D	laboratory	7.420 (σ = 0.099)	15	Asplund et al. (2000) (A00)	7.450 (σ = 0.043)
HM	theoretical	7.490 (σ = 0.083)	39	Biemont et al. (1991) (B91)	7.490 (σ = 0.047)

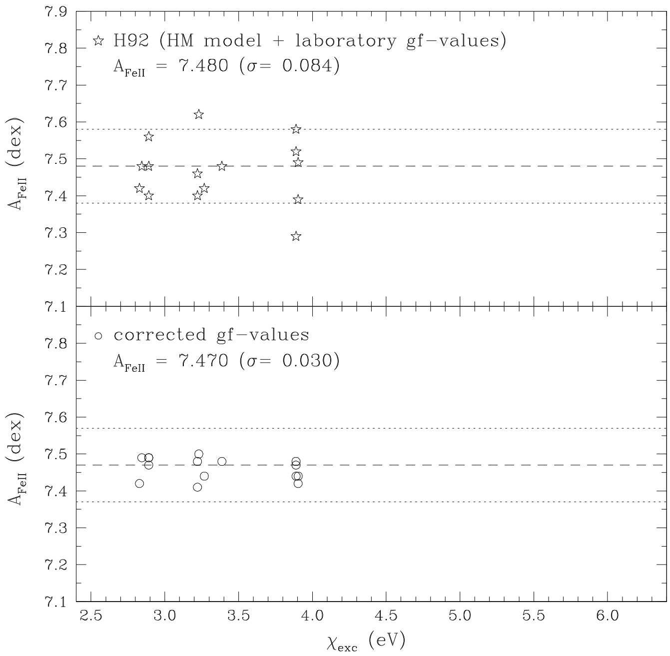

Fig. 1. Iron abundances from Fe II lines obtained by Hannaford et al. (1992) using their laboratory gf-values (*upper panel*) and re-scaled abundances using our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

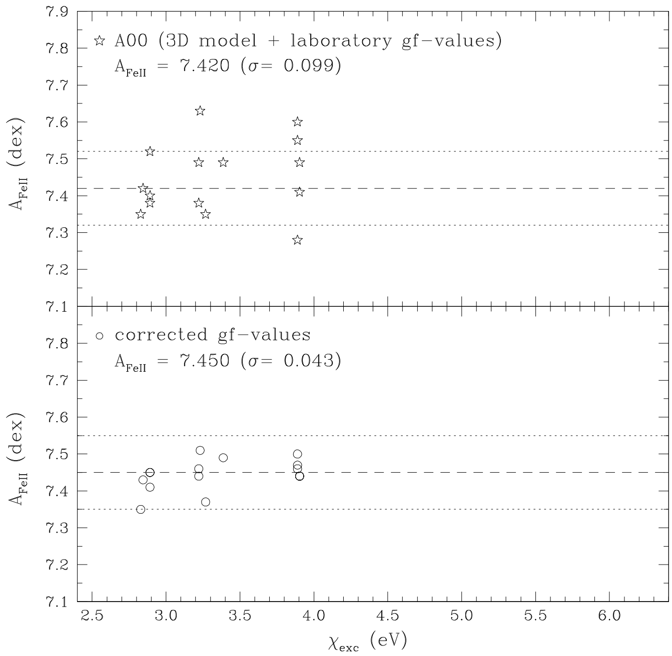

Fig. 3. Iron abundances from Fe II lines obtained by Asplund et al. (2000) using the Hannaford et al. (1992) laboratory gf-values (*upper panel*) and re-scaled abundances using our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

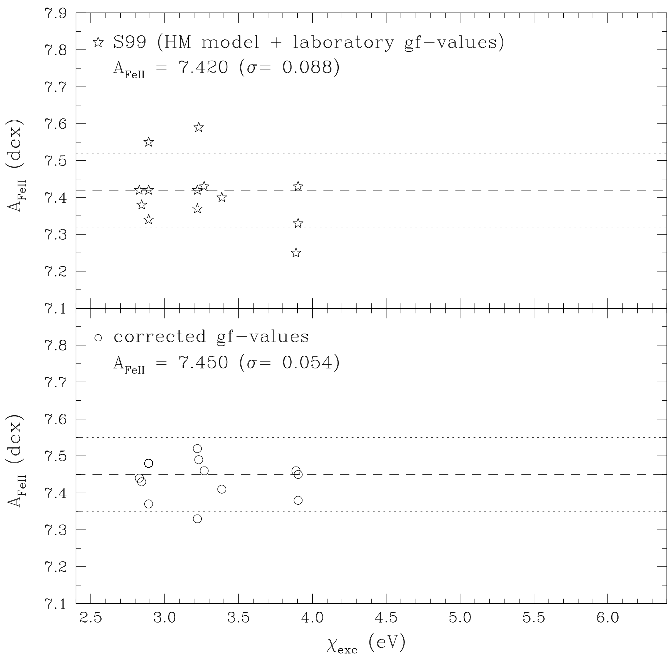

Fig. 2. Iron abundances from Fe II lines obtained by Schnabel et al. (1999) using their laboratory gf-values (*upper panel*) and re-scaled abundances using our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

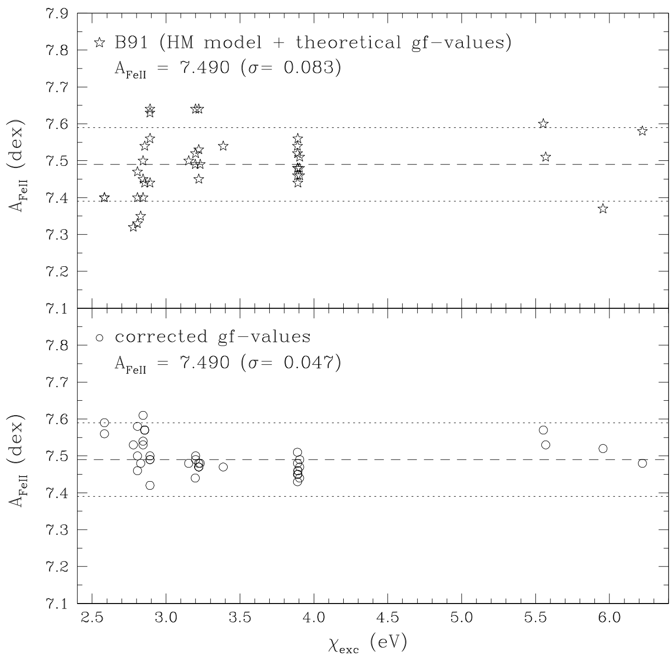

Fig. 4. Iron abundances from Fe II lines obtained by Biémont et al. (1991) using theoretical gf-values (*upper panel*) and re-scaled abundances using our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

Table 3. Centre-of-the-disk equivalent widths used to determine the solar iron abundance from different model atmospheres (Table 4).

λ (Å)	EW (mÅ)
4576.340	67.0
4620.521	55.4
4656.981	35.6
5234.625	88.3
5264.812	47.5
5414.073	27.9
5525.125	12.7
5627.497	8.1
6432.680	43.4
6516.080	57.0
7222.394	20.3
7224.487	20.9
7449.335	19.4
7515.832	15.0
7711.724	50.1

The EW are the average values presented in Holweger et al. (1990), Biémont et al. (1991), Hannaford et al. (1992), and Grevesse & Sauval (1999).

Table 4. Solar iron abundances based on 15 Fe II lines (Table 3) with our gf-values and different model atmospheres.

Model	$v_{\rm mic}$ (km s^{-1})	$A_{\rm FeII}(\sigma)$ (dex)
HM	1.09	7.46 (σ = 0.028)
Kurucz OVER	0.98	7.48 (σ = 0.026)
Kurucz NOVER	0.91	7.43 (σ = 0.027)
MARCS 1997	0.92	7.44 (σ = 0.029)
MARCS 2008	0.91	7.42 (σ = 0.028)
⟨3D⟩	0.92	7.47 (σ = 0.027)
3D		7.45 (re-scaled from A00)
mean		7.45 (σ = 0.022)

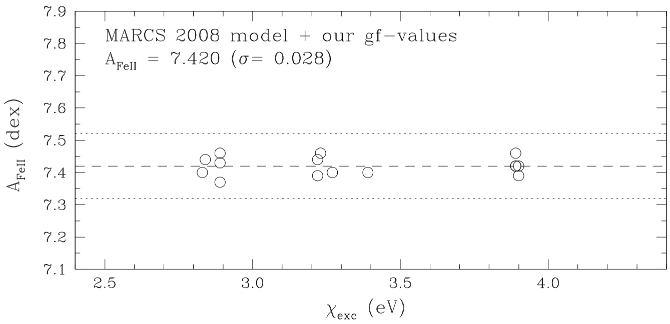

Fig. 5. Iron abundances based on 15 Fe II lines with our gf-values and the MARCS 2008 solar model atmosphere. Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

observed for the determination of isotopic lithium abundances and tests of stellar parameters and model atmospheres will be presented in Asplund & Meléndez (2009, in preparation) and Meléndez et al. (2009, in preparation).

The spectra of HD 140283 and HD 148816 were scrutinized for relatively clean Fe II lines, resulting in a total of 27 different lines appropriate for analysis, with 20 suitable lines available in HD 140283 and 23 in HD 148816. In Table 5 we show the equivalent widths measured using IRAF. The calculations were performed using the 2002 version of MOOG (Sneden 1973) and employing Kurucz overshooting model atmospheres. The stellar parameters were determined following Meléndez et al. (2006a)

Table 5. Equivalent widths (mÅ) for Fe II lines in HD 148816 and HD 140283.

λ(Å)	HD 148816	HD 140283
4128.75	26.6	–
4178.86	68.5	17.8
4233.17	–	41.3
4416.83	61.6	10.3
4489.18	45.5	5.1
4491.40	54.8	7.1
4508.29	68.0	15.8
4515.34	58.5	11.6
4520.22	61.0	11.3
4522.63	–	22.1
4541.52	45.3	5.2
4555.89	73.0	15.6
4576.34	45.0	4.5
4582.84	36.6	2.8
4583.84	–	37.0
4731.45	–	3.5
4923.93	126.5	57.0
5018.44	140.5	67.0
5197.58	62.2	10.7
5234.62	66.2	12.6
5264.81	27.3	–
5284.11	36.4	–
5414.07	12.0	–
5425.26	22.1	–
6369.46	7.4	–
6432.68	21.8	–
6516.08	32.0	2.2

Table 6. Iron abundances from Fe II lines in the metal-poor stars HD 148816 and HD 140283.

Star	$T_{\rm eff}$/ log g/$v_{\rm mic}$ (K/dex/km s^{-1})	our line list $A_{\rm FeII}$ (σ) (dex)	FW06 $A_{\rm FeII}$ (σ) (dex)	n
HD 148816	5825/4.14/1.20	6.72 (0.04)	6.67 (0.18)	23
HD 140283	5717/3.70/1.35	5.10 (0.05)	5.00 (0.11)	20

and are presented in Table 6. Since here we are interested in the line-to-line scatter due to errors in the gf-values, the specific choice of model atmosphere and stellar parameters is irrelevant. In addition to the test of our gf-values, we also tested the critical compilation of atomic transition probabilities by Fuhr & Wiese (2006).

The results are shown in Table 6 and Figs. 6 and 7. As can be seen, the present line list is precise, providing a line-to-line scatter in the iron abundance as low as 0.04 dex in the case of HD 148816, while for the same star the line list of Fuhr & Wiese (2006) provides an uncomfortably large scatter of 0.18 dex. For star HD 140283, which is much more metal-poor, the scatter obtained with our line list is 0.01 dex higher than for the moderately metal-poor star HD 148816, as expected due to the faintness of some Fe II lines in HD 140283. Our scatter of 0.05 dex for HD 140283 is considerably lower than the scatter of 0.11 dex obtained from the FW06 compilation. The performance of the FW06 line list is much worse for HD 148816 (σ = 0.18 dex) than for HD 140283 (σ = 0.11 dex), while in our case the performance was about the same (σ = 0.04 and 0.05 dex). Thus, our line list is almost immune to the particular choice of lines and can be safely applied even when only a few lines are available for analysis.

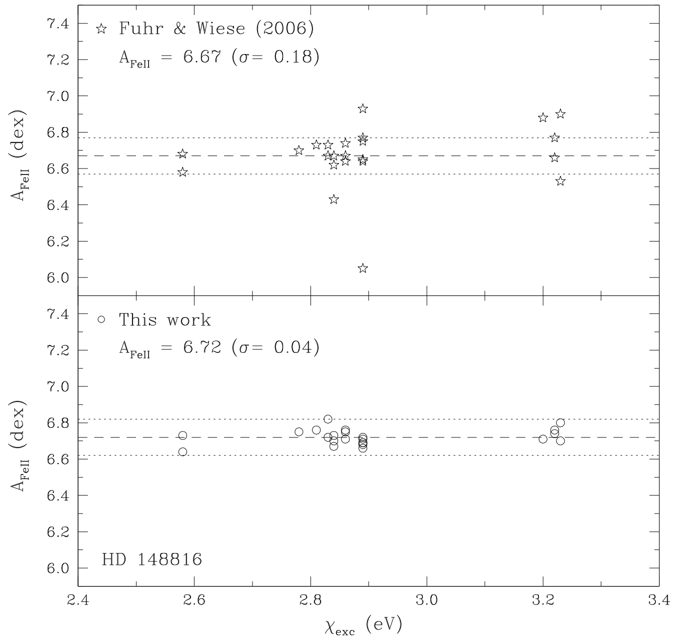

Fig. 6. Iron abundances in HD 148816 from 23 Fe II lines using the Fuhr & Wiese (2006) oscillator strengths (*upper panel*) and our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

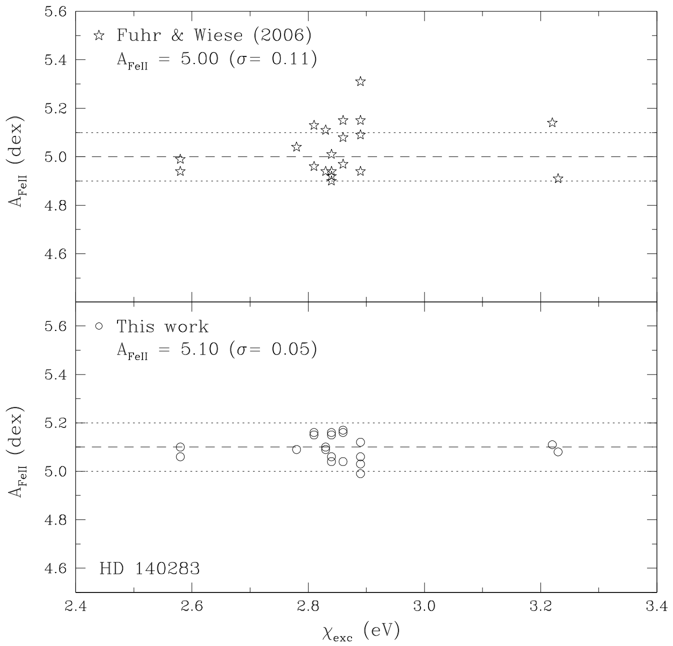

Fig. 7. Iron abundances in HD 140283 from 20 Fe II lines using the Fuhr & Wiese (2006) oscillator strengths (*upper panel*) and our improved gf-values (*lower panel*). Dashed and dotted lines are shown at the median value and ±0.1 dex, respectively.

5. Comparison with other line lists

In their work on RR Lyrae stars, Lambert et al. (1996) performed a critical selection of oscillator strengths for Fe II lines based on a combination of laboratory, theoretical, and solar gf-values. The agreement with our work is very good, with a mean difference of only –0.01 dex (this work – Lambert et al.) and σ = 0.06 dex.

We also compared our gf-values with other values in the literature. This is shown in Table 7, where the mean difference, the line-to-line scatter (σ), and the number of lines in common are given for 18 different works in the literature. As can be seen, the gf-values adopted by most works have a zero-point in agreement with ours within 0.02 dex, but in some cases the standard deviation is too great (Aoki et al. 2005; Ivans et al. 2006). In other cases, both the mean difference and scatter are too large (Blackwell et al. 1980; Bensby et al. 2003; François et al. 2003).

Table 7. Mean difference between our log gf values and those adopted in the literature.

Reference	This work – literature	# lines
Blackwell et al. (1980)	0.15 (σ = 0.09)	41
Gurtovenko & Kostik (1989)	0.21 (σ = 0.05)	55
Lambert et al. (1996)	–0.01 (σ = 0.06)	24
Fulbright (2000)	–0.01 (σ = 0.07)	26
Bensby et al. (2003)	0.11 (σ = 0.08)	37
Chen et al. (2003)	0.07 (σ = 0.04)	16
François et al. (2003)	–0.09 (σ = 0.12)	12
Gratton et al. (2003)	–0.02 (σ = 0.08)	42
Gratton et al. (2003) (λ > 4600 Å)	0.00 (σ = 0.06)	34
Korn et al. (2003)	0.05 (σ = 0.07)	35
Reddy et al. (2003)	–0.01 (σ = 0.04)	9
Sneden et al. (2003)	0.02 (σ = 0.09)	11
Nissen et al. (2004)	0.04 (σ = 0.06)	19
Santos et al. (2004)	0.01 (σ = 0.03)	12
Aoki et al. (2005)	0.01 (σ = 0.11)	19
Sadakane et al. (2005)	0.02 (σ = 0.06)	11
Ivans et al. (2006)	0.02 (σ = 0.11)	19
Randich et al. (2006)	0.06 (σ = 0.06)	10
Sousa et al. (2008)	0.00 (σ = 0.07)	31

The large difference in zero point with both Blackwell et al. (1980) and Gurtovenko & Kostik (1989) stem from a much higher solar iron abundance used by them in their derivation of solar oscillator strengths. The Gurtovenko & Kostik (1989) set of solar gf-values seems precise (σ = 0.05), with even lower scatter than the set of solar gf-values recently obtained by Sousa et al. (2008).

The large difference in zero point with the gf-values used by Bensby et al. (2003) is due to their use of uncorrected theoretical oscillator strengths by Raassen & Uylings (1998). The log gf-value of the 4993.36 Å Fe II line given in Bensby et al. is incorrectly quoted as –3.52. (Actually this is the value given by Raassen & Uylings for the 4992.47 Å line.) According to Raassen & Uylings (1998), log gf = –3.68 for the 4993.36 Å line. Besides the zero-point issue, the scatter of the gf-values used by Bensby et al. is also relatively large (σ = 0.08 dex). Thus, the Raassen & Uylings (1998) oscillator strengths are not recommended due to both their inaccuracy and imprecision. This set of gf-values has been also used by Lecureur et al. (2007) in the analysis of metal-rich Bulge giants. Care should be taken when studying such metal-rich cool giants, because very few unblended Fe II lines are available for analysis, making the use of a precise line list mandatory.

The oscillator strengths by Chen et al. (2003), Reddy et al. (2003), and Santos et al. (2004) show the lowest scatter (σ = 0.03–0.04 dex) with respect to our gf-values, but the Chen et al. (2003) oscillator strengths have a large zero-point difference (0.07 dex).

6. Conclusions

We have obtained accurate and precise oscillator strengths for Fe II lines. Our gf-values were tested using the Sun and the metal-poor stars HD 148816 and HD 140283, for which standard deviations of $\sigma = 0.03$, 0.04, and 0.05 dex are found, respectively. The standard error for the mean iron abundance is negligible ($\sigma_{\mathrm{mean}} \leq 0.01$ dex), and therefore the error in gf-values of Fe II lines is no longer a limitation for high-precision stellar abundance work. Now the main uncertainties related to determining iron abundances are the adopted stellar parameters, line formation treatment, model atmospheres, blends, and errors in the measurement of equivalent widths (or spectral synthesis fitting).

Acknowledgements. We thank the referee (Prof. D. Lambert) for his constructive comments. This work has been partially supported by FAPESP (2005/00397-1) and CNPq (Brazil), and FCT (project PTDC/CTE-AST/65971/2006, and Ciencia 2007 program).

References

Allen, D. M., & Barbuy, B. 2006, A&A, 454, 895
Alves-Brito, A., Barbuy, B., Ortolani, S., et al. 2005, A&A, 435, 657
Alves-Brito, A., Barbuy, B., Zoccali, M., et al. 2006, A&A, 460, 269
Aoki, W., Honda, S., Beers, T. C., et al. 2005, ApJ, 632, 611
Asplund, M. 2005, ARA&A, 43, 481
Asplund, M., Gustafsson, B., Kiselman, D., & Eriksson, K. 1997, A&A, 318, 521
Asplund, M., Nordlund, Å., Trampedach, R., & Stein, R. F. 2000, A&A, 359, 743 (A00)
Asplund, M., Grevesse, N., Sauval, A. J., Allende Prieto, C., & Kiselman, D. 2004, A&A, 417, 751
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ASP Conf. Ser. 336, 25
Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, ApJ, 644, 229
Barbuy, B., Zoccali, M., Ortolani, S., et al. 2006, A&A, 449, 349
Barbuy, B., Zoccali, M., Ortolani, S., et al. 2007, AJ, 134, 1613
Barklem, P. S., & Aspelund-Johansson, J. 2005, A&A, 435, 373
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Biémont, E., Baudoux, M., Kurucz, R. L., Ansbacher, W., & Pinnington, E. H. 1991, A&A, 249, 539 (B91)
Blackwell, D. E., Shallis, M. J., & Simmons, G. J. 1980, A&A, 81, 340
Castelli, F., & Kurucz, R. L. 2004, A&A, 419, 725
Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, A&A, 318, 841
Chen, Y. Q., Zhao, G., Nissen, P. E., Bai, G. S., & Qiu, H. M. 2003, ApJ, 591, 925
Coelho, P., Barbuy, B., Meléndez, J., Schiavon, R. P., & Castilho, B. V. 2005, A&A, 443, 735
François, P., Depagne, E., Hill, V., et al. 2003, A&A, 403, 1105
Fuhr, J. R., & Wiese, W. L. 2006, J. Phys. Chem. Ref. Data, 35, 1669 (FW06)
Fulbright, J. P. 2000, AJ, 120, 1841
Gehren, T., Butler, K., Mashonkina, L., Reetz, J., & Shi, J. 2001, A&A, 366, 981
Goldbach, C., Martin, M., & Nollez, G. 1989, A&A, 221, 155
Gratton, R. G., Carretta, E., Claudi, R., et al. 2003, A&A, 404, 187
Gray, D. F. 2005, The Observation and Analysis of Stellar Photospheres, 3rd edn (Cambridge, UK: Cambridge University Press)
Grevesse, N., & Sauval, A. J. 1999, A&A, 347, 348
Guo, B., Ansbacher, W., Pinnington, E. H., Ji, Q., & Berends, R. W. 1992, Phys. Rev. A, 46, 641
Gurtovenko, E. A., & Kostik, R. I. 1989, Fraunhofer Spectrum and the System of Solar Oscillator Strenghts (Kiev: Noukova Dumka)
Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951
Hannaford, P. 1994, Spectrochim. Acta, 49, 1581
Hannaford, P., Lowe, R. M., Grevesse, N., & Noels, A. 1992, A&A, 259, 301 (H92)
Heise, C., & Kock, M. 1990, A&A, 230, 244
Hekker, S., & Meléndez, J. 2007, A&A, 475, 1003
Hinkle, K., Wallace, L., Valenti, J., & Harmer, D. 2000, Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 A ed. K. Hinkle, L. Wallace, J. Valenti, & D. Harmer (San Francisco: ASP)
Holweger, H., & Müller, E. A. 1974, Sol. Phys., 39, 19 (HM)
Holweger, H., Heise, C., & Kock, M. 1990, A&A, 232, 510
Ivans, I. I., Simmerer, J., Sneden, C., et al. 2006, ApJ, 645, 613
Korn, A. J., Shi, J., & Gehren, T. 2003, A&A, 407, 691
Kraft, R. P., & Ivans, I. I. 2003, PASP, 115, 143
Kroll, S., & Kock, M. 1987, A&AS, 67, 225
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, National Solar Observatory Atlas, Sunspot, New Mexico: National Solar Observatory
Lambert, D. L., Heath, J. E., Lemke, M., & Drake, J. 1996, ApJS, 103, 183
Lecureur, A., Hill, V., Zoccali, M., et al. 2007, A&A, 465, 799
Meléndez, J., & Barbuy, B. 2002, ApJ, 575, 474
Meléndez, J., Shchukina, N. G., Vasiljeva, I. E., & Ramírez, I. 2006a, ApJ, 642, 1082
Meléndez, J., Dodds-Eden, K., & Robles, J. A. 2006b, ApJ, 641, L133
Meléndez, J., Asplund, M., Gustafsson, B., & Yong, D. 2009, submitted
Nissen, P. E., Primas, F., Asplund, M., & Lambert, D. L. 2002, A&A, 390, 235
Nissen, P. E., Chen, Y. Q., Asplund, M., & Pettini, M. 2004, A&A, 415, 993
Nissen, P. E., Akerman, C., Asplund, M., et al. 2007, A&A, 469, 319
Pauls, U., Grevesse, N., & Huber, M. C. E. 1990, A&A, 231, 536
Pickering, J. C., Johansson, S., & Smith, P. L. 2001, A&A, 377, 361
Raassen, A. J. J., & Uylings, P. H. M. 1998, A&A, 340, 300
Ramírez, I., Allende Prieto, C., Redfield, S., & Lambert, D. L. 2006, A&A, 459, 613
Ramírez, I., Allende Prieto, C., & Lambert, D. L. 2007, A&A, 465, 271
Randich, S., Sestito, P., Primas, F., Pallavicini, R., & Pasquini, L. 2006, A&A, 450, 557
Reddy, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003, MNRAS, 340, 304
Sadakane, K., Ohnishi, T., Ohkubo, M., & Takeda, Y. 2005, PASJ, 57, 127
Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153
Santos, N. C., Lovis, C., Pace, G., Melendez, J., & Naef, D. 2009, A&A, 493, 309
Schnabel, R., & Kock, M. 2001, Phys. Rev. A, 63, 012519
Schnabel, R., Kock, M., & Holweger, H. 1999, A&A, 342, 610 (S99)
Schnabel, R., Schultz-Johanning, M., & Kock, M. 2004, A&A, 414, 1169
Shchukina, N., & Trujillo Bueno, J. 2001, ApJ, 550, 970
Shchukina, N. G., Trujillo Bueno, J., & Asplund, M. 2005, ApJ, 618, 939
Smiljanic, R., Barbuy, B., de Medeiros, J. R., & Maeder, A. 2006, A&A, 449, 655
Smiljanic, R., Gauderon, R., North, P., et al. 2008, A&A, submitted [arXiv:0810.1701]
Sneden, C. A. 1973, Ph.D. Thesis, The University of Texas at Austin
Sneden, C., Cowan, J. J., Lawler, J. E., et al. 2003, ApJ, 591, 936
Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, A&A, 487, 373
Spite, M. 1967, Annales d'Astrophysique, 30, 211
Thévenin, F., & Idiart, T. P. 1999, ApJ, 521, 753
Vogt, S. S., Allen, S. L., Bigelow, B. C., et al. 1994, Proc. SPIE, 2198, 362
Yong, D., Lambert, D. L., Allende Prieto, C., & Paulson, D. B. 2004, ApJ, 603, 697
Zoccali, M., Barbuy, B., Hill, V., et al. 2004, A&A, 423, 507