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Fe I oscillator strengths for lines with excitation energies between 3 and 7 eV

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Abstract. Oscillator strengths of 116 Fe I lines were obtained from a combination of lifetimes measured with the laser induced fluorescence (LIF) technique and branching ratios obtained from Fourier-transform and grating spectra. Lines covering a range of excitation energies from 25 000 to 54 000 cm^{-1} were chosen to enlarge the set of suitable lines for solar and stellar abundance studies. The overall uncertainties of the f-values are typically between 7% and 12%, and 29% at the most. The data are compared with literature values. The present study is a continuation of recently published Fe I measurements.

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

1. Introduction

Although a growing number of Fe I oscillator strengths is available in the literature, those which are suitable for solar or stellar abundance studies are rather scarce. Especially, f-values of lines with small equivalent widths are of special astrophysical interest. A list of such lines can be found in the papers of Holweger (1967) and Ruland et al. (1980).

The present work is a continuation of measurements on Fe I (Bard et al. 1991) aimed at enlarging the set of f-values suitable for a reliable solar iron abundance determination, and hence at resolving the large discrepancy in the iron abundance found in the literature (Holweger et al. 1990, 1991). To this end a set of data pertaining to lines having small equivalent widths in the solar spectrum and covering an excitation range as large as possible is highly desirable.

As in our previous Fe I paper we have combined lifetime with branching ratio measurements, a procedure which excludes nearly all systematic error sources. The atomic lifetimes have been measured with the laser-induced fluorescence technique (Engelke et al. 1993) whereas the branching ratios are determined from Fourier-transform spectra and grating spectra. A high-current hollow-cathode was used as the light source.

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The result of the present work is a set of 50 Fe I lines now available for a more solid solar iron abundance analysis.

2. Experimental procedure

As in our previous paper (Bard et al. 1991) we combined measurements of lifetimes and branching ratios (see, e.g., Huber & Sandeman 1988). A detailed description of the methods applied in this paper is given by Bard (1993).

For the lifetime measurements we used the time-resolved laser-induced fluorescence technique. A beam of iron atoms from a hollow cathode discharge was excited with a tunable dye laser pulse and the fluorescence was measured by means of a fast transient digitizer with an analog bandwidth of 1 GHz. The procedure and part of the lifetime data are published elsewhere (Engelke et al. 1993).

The branching ratios are determined by emission measurements on a high-current hollow-cathode (HC) as described by Danzmann et al. (1988). The discharge was operated in argon or neon (0.4–4 hPa) at currents between 0.2 and 3 A and at voltages between 150 and 700 V. The iron atoms were sputtered from a metallic cylinder made of very pure iron (VP 99.95%).

Part of the measurements have been performed with the high-resolution Fourier-transform spectrometer (Brault 1985) at Kitt Peak, Arizona. By adding up several runs and by using band pass filters the S/N ratio in the spectra could be increased considerably. The line intensities were calibrated with a tungsten strip lamp (Optronics) and with a deuterium lamp (Cathodeon).

At moderate currents faint lines often are not detectable in the HC. Strong lines tend to be self-absorbed, also self-reversed, even at low currents. In those cases we measured the lines in our laboratory using a 2 m McPherson monochromator in Czerny–Turner mount with a grating 2400 lines per mm giving an apparatus profile with 45 mÅ full halfwidth.

The influence of self-absorption in the lines was checked with two different methods:

(i) By varying the discharge current the intensity ratio of lines with a common upper level has to be constant.

This method has been applied to measurements in our laboratory because we were not able to resolve the line profiles with our grating monochromator. The branching ratios become independent of the discharge current at 0.2 A for all lines. To minimize the effect of slow intensity variations of the light source we always measured pairs of lines in an alternating sequence. A minimum of nine independent measurements is taken for one pair of lines.

(ii) With the Fourier-transform spectrometer (FTS) the lines are indeed resolved. The purely Doppler broadened lines as emitted from our HC can thus be fitted by a Gauss profile and be used for a test: Lines affected by self-absorption are broadened with respect to optically thin lines. If necessary the intensities have been corrected to optically thin layer by the following formula:

$$I_c = I\alpha/[1-\exp(-\alpha)]\,,$$

where α is the measured optical depth. The maximum correction for line intensity was no more than 10% for a few critical lines.

The transition probabilities (f-values) of all lines originating from a common upper level are converted to absolute values by using the radiative lifetime of this particular level. In Table 1 the lifetime data are listed together with the absolute transition probabilities.

3. Data reduction

The Fe I spectra were analysed by means of the tables given by Moore (1952). We used the semiempirical calculations by Kurucz & Peytremann (1975) to search for blends and for checking the contributions of faint lines not measured in an actual run.

Table 1. Absolute oscillator strength for Fe I

λ (nm)	Transition	E_i (cm^{-1})	A_{ki} ($10^4\ s^{-1}$)	log(gf)	Error (%)
$y^5D^\circ_2$, $E_k = 33801.595\ cm^{-1}$, $\tau_k = 6.4 \pm 0.3$ ns					
299.4424	a^5D_3	415.933	4060	−0.564	11
302.0488	a^5D_2	704.003	2080	−0.846	11
303.7386	a^5D_1	888.132	3390	−0.630	11
383.4220	a^5F_3	7728.071	4930	−0.265	9
387.2499	a^5F_2	7985.795	1080	−0.917	9
389.8006	a^5F_1	8154.725	88.6	−1.996	9
615.1619	a^5P_3	17550.210	19.2	−3.265	9
621.9282	a^5P_2	17727.017	13.1	−2.422	9
629.7794	a^5P_1	17927.411	6.30	−2.727	9
648.1872	a^3P_2	18378.215	3.48	−2.960	9
$y^3D^\circ_3$, $E_k = 38175.38\ cm^{-1}$, $\tau_k = 6.9 \pm 0.5$ ns[d]					
261.8708	a^5D_4	0.000	121	−2.060**	12
264.7555	a^5D_3	415.933	147	−1.966	12
266.7910	a^5D_2	700.003	32.7	−2.613	16
381.5839	a^3F_4	11976.260	11300	0.236	10
390.2944	a^3F_3	12560.953	2470	−0.404	10
396.6060	a^3F_2	12968.573	194	−1.494	10
488.9001	a^5P_2	17727.017	16.7	−2.377	11
504.9820	a^3P_2	18378.215	173	−1.334	10
570.1546	b^3F_4	20641.144	22.2	−2.120	10
577.8457	b^3F_3	20874.521	1.06	−3.430	12
618.0206	a^3G_4	21999.167	6.48	−2.586	10
651.8370	b^3P_2	22838.360	7.96	−2.450	10
711.2172	b^3G_4	24118.854	1.93	−2.990	24
722.3663	c^3P_2	24335.804	11.1	−2.215	10
836.5655	a^3D_3	26225.030	12.5	−2.037	16
$y^3D^\circ_2$, $E_k = 38678.067\ cm^{-1}$, $\tau_k = 6.9 \pm 0.3$ ns[a,c]					
261.2770	a^5D_3	415.933	116	−2.226**	13
263.2591	a^5D_2	704.003	166	−2.064**	12
264.5419	a^5D_1	888.132	49.2	−2.588**	15
382.7830	a^3F_3	12560.953	11200	0.090	10
388.8520	a^3F_2	12968.573	2660	−0.520	10
477.1696	a^5P_2	17727.017	3.42	−3.234	20
492.4769	a^3P_2	18378.215	31.6	−2.241	11

Table 1 (continued)

λ (nm)	Transition	E_i (cm^{-1})	A_{ki} ($10^4\ s^{-1}$)	log(gf)	Error (%)
522.7146	a^3P_1	19552.493	217	− 1.352	23
561.5300	b^3F_3	20874.521	15.4	− 2.438	10
608.5256	a^3G_3	22249.461	2.89	− 3.095	12
631.1503	b^3P_2	22838.360	2.42	− 3.141	10
635.5034	b^3P_1	22946.860	14.7	− 2.350	10
697.1937	b^3G_3	24338.805	1.25	− 3.340*	15
718.9155	c^3P_1	24772.060	4.38	− 2.771*	13
829.3490	a^3D_2	26623.730	13.0	− 2.175	18
e^7D_5, E_k = 42815.855 cm^{-1}, τ_k = 7.9 ± 0.4 ns[a]					
426.0474	$z^7D_5^\circ$	19350.894	4630	0.141	7
429.9237	$z^7D_4^\circ$	19562.457	1480	− 0.346	7
495.7598	$z^7F_6^\circ$	22650.427	4220	0.232	7
500.6121	$z^7F_5^\circ$	22845.880	527	− 0.662	7
504.4213	$z^7F_4^\circ$	22996.686	20.8	− 2.059	7
523.2942	$z^7P_4^\circ$	23711.467	1770	− 0.096	7
590.9976	$z^5D_4^\circ$	25900.002	4.49	− 2.587	7
627.1282	$z^5F_5^\circ$	26874.562	3.05	− 2.703	8
e^5D_1, E_k = 45509.155 $^{-1}$, τ_k = 15.2 ± 0.8 ns					
521.5182	$z^5D_2^\circ$	26339.708	1100	− 0.871	7
525.3464	$z^5D_1^\circ$	26479.393	215	− 1.573	7
527.3166	$z^5D_0^\circ$	26550.495	812	− 0.993	7
556.9621	$z^5F_2^\circ$	27559.598	2340	− 0.486	7
560.2948	$z^5F_1^\circ$	27666.362	1000	− 0.850	7
623.2642	$z^5P_2^\circ$	29469.033	342	− 1.223	7
633.6827	$z^5P_1^\circ$	29732.749	770	− 0.856	7
$w^3D_1^\circ$, E_k = 47272.095 cm^{-1}, τ_k = 15.1 ± 0.8 ns[a]					
291.4299	a^3F_2	12968.573	294	− 1.949	11
338.3687	a^5P_2	17727.017	716	− 1.433	9
340.6794	a^5P_1	17927.411	1730	− 1.044	9
345.9949	a^3P_2	18378.215	47.7	− 2.590	17
360.6526	a^3P_1	19552.493	125	− 2.135	14
367.0803	a^3P_0	20037.860	184	− 1.952	10
409.1547	b^3P_2	22838.360	113	− 2.068	9
410.9797	b^3P_1	22946.860	1670	− 0.895	8
412.7602	b^3P_0	23051.790	1600	− 0.911	8
479.1236	a^3D_1	26406.490	35.5	− 2.435	10
740.1658	c^3F_2	33765.330	102	− 1.599	12
$w^5G_4^\circ$, E_k = 47590.070 cm^{-1}, τ_k = 34.6 ± 1.7 ns[a]					
248.5989	a^5F_4	7376.775	272	− 1.644	10
250.7899	a^5F_3	7728.071	1950	− 0.782	10
359.5864	a^3H_4	19788.280	26.7	− 2.331	11
370.9667	b^3F_4	20641.144	111	− 1.687	9
386.3743	a^3G_5	21715.770	198	− 1.400	8
394.5118	a^3G_3	22249.461	203	− 1.370	8
425.9338	b^3G_4	24118.854	4.19	− 2.989	24
429.9631	b^3G_3	24338.805	26.4	− 2.180	9
434.3699	a^1G_4	24574.690	62.1	− 1.801	8
467.9233	a^3D_3	26225.030	12.9	− 2.418	9
532.6143	a^1H_5	28819.980	22.2	− 2.071	9
679.3269	c^3F_4	32873.680	7.57	− 2.326	10
$^1H_5^\circ$, E_k = 51630.172 cm^{-1}, τ_k = 24.5 ± 1.2 ns					
310.0839	a^3H_6	19390.197	313	− 1.304	10
322.6017	b^3F_4	20641.144	56.5	− 2.013	11
334.1910	a^3G_5	21715.770	275	− 1.295	9

Table 1 (continued)

λ (nm)	Transition	E_i (cm^{-1})	A_{ki} (10^4 s^{-1})	log(gf)	Error (%)
337.3874	a^3G_4	21999.167	27.2	−2.292	13
359.0088	b^3G_5	23783.654	88.3	−1.726	11
363.3831	b^3G_4	24118.854	133	−1.539	10
369.5056	a^1G_4	24574.690	1780	−0.397	9
391.6737	b^3H_6	26105.950	1080	−0.565	8
438.2773	a^1H_5	28819.980	182	−1.239	8
533.0004	c^3F_4	32873.680	138	−1.189	8
685.4857	d^3F_4	37046.000	15.3	−1.926	9
$u^3G_4^\circ$, E_k = 51668.175 cm^{-1}, τ_k = 13.5 ± 0.7 ns[a]					
255.6302	a^3F_3	12560.953	394	−1.459	18
311.9494	a^3H_5	19621.036	987	−0.887	10
313.5860	a^3H_4	19788.280	48.6	−2.190	26
324.6481	b^3F_3	20874.521	271	−1.414	10
333.7665	a^3G_5	21715.770	534	−1.095	10
336.9547	a^3G_4	21999.167	1920	−0.530	10
339.8216	a^3G_3	22249.461	61.5	−2.018	12
358.5190	b^3G_5	23783.654	245	−1.370	10
362.8813	b^3G_4	24118.854	35.0	−2.206	19
365.8019	b^3G_3	24338.805	56.3	−1.993	15
392.9212	a^3D_3	26225.030	235	−1.309	8
394.8777	b^3H_5	26351.090	2230	−0.328	8
437.5475	a^1H_5	28819.980	15.3	−2.402	18
547.6297	c^3F_3	33412.780	311	−0.900	8
680.4278	d^3F_3	36975.640	24.6	−1.813	10
683.7020	d^3F_4	37046.000	32.6	−1.687	10
$u^3D_3^\circ$; E_k = 51969.140 cm^{-1}, τ_k = 9.30 ± 0.5 ns					
297.6125	a^3P_2	18378.215	1160	−0.968	10
319.1110	b^3F_4	20641.144	133	−1.846	14
343.1811	b^3P_2	22838.360	489	−1.218	10
358.9603	b^3G_4	24118.854	92.7	−1.901	15
361.7785	c^3P_2	24335.804	6530	−0.047	10
364.9334	a^1G_4	24574.690	131	−1.737	29
388.3283	a^3D_3	26225.030	1570	−0.604	9
394.4979	b^3H_4	26627.640	56.9	−2.031	29
442.4069	b^3D_3	29371.860	23.7	−2.312	21
523.5389	c^3F_4	32873.680	486	−0.854	9
538.7489	c^3F_3	33412.780	30.3	−2.034	12
549.1829	c^3F_2	33765.330	20.5	−2.188	14
666.7715	d^3F_3	36975.640	16.5	−2.112	17
669.9153	d^3F_4	37046.000	16.8	−2.101	15
g^5D_1, E_k = 52214.330 cm^{-1}, τ_k = 12.1 ± 0.6 ns					
386.3695	$z^5D_2^\circ$	26339.708	437	−1.532	9
389.5430	$z^5D_0^\circ$	26550.495	337	−1.637	12
405.4871	$z^5F_2^\circ$	27559.598	962	−1.148	8
407.2507	$z^5F_1^\circ$	27666.362	487	−1.439	9
439.5278	$z^5P_2^\circ$	29469.033	170	−1.830	10
444.6837	$z^5P_1^\circ$	29732.749	539	−1.320	8
487.0046	$z^3D_2^\circ$	31686.377	38.7	−2.383	16
493.0324	$z^3D_1^\circ$	31937.350	576	−1.201	8
497.8612	$z^3F_2^\circ$	32134.014	1190	−0.877	8
542.9514	$y^5D_2^\circ$	33801.595	727	−1.016	13
547.2722	$z^3P_2^\circ$	33946.965	237	−1.495	8
552.5554	$y^5D_0^\circ$	34121.623	600	−1.084	8
560.0234	$z^3P_1^\circ$	34362.890	270	−1.420	8
565.8669	$y^5F_2^\circ$	34547.235	452	−1.186	11

Table 1 (continued)

λ (nm)	Transition	E_i (cm^{-1})	A_{ki} ($10^4\ s^{-1}$)	log(gf)	Error (%)
566.1363	$z^3P^\circ_0$	34555.640	122	−1.756	9
570.5476	$y^5F^\circ_1$	34692.172	302	−1.355	9
675.2722	$y^5P^\circ_1$	37409.575	305	−1.204	9
680.4017	$y^3F^\circ_2$	37521.186	153	−1.496	10
892.9094	$x^5F^\circ_2$	41018.060	356	−0.893	13
e^5H_4, $E_k = 54237.200\ cm^{-1}$, $\tau_k = 12.9 \pm 0.6\ ns$[b]					
502.1598	$y^5F^\circ_3$	34328.775	343	−0.932	7
526.7278	$z^5G^\circ_4$	35257.345	67.6	−1.596	11
536.7476	$z^5G^\circ_3$	35611.649	7180	0.445	7
541.2795	$z^3G^\circ_4$	35767.591	48.5	−1.716	9
569.6101	$y^3F^\circ_4$	36686.204	43.5	−1.720	11
585.5087	$y^3F^\circ_3$	37162.770	71.9	−1.478	9

[a] Engelke et al. (1993)
[b] O'Brian et al. (1991)
[c] Branching ratios from Bard et al. (1991) except the two freshly measured lines marked by *.
[d] Kwiatkowski et al. (1983). The level is already given in Bard et al. (1991). The only change is the line marked **.
** Line was recalculated due to a computational error in Bard et al. (1991). All lines belonging to the upper level are rescaled with respect to the new value.
All lifetimes which are not labeled are measured in Bard (1993) or in this work.

For the highly resolved FTS spectra the area under a line, which is a measure for the total line intensity, was determined by a least-squares fit of a Gaussian function to the line profile which is almost totally Doppler broadened. For some spectra with medium resolution the apparatus function of the FTS has been taken into account.

A Gaussian function fits the measured lines well even though the HC lines were not resolvable at the 45 mÅ halfwidth of the apparatus function of our grating monochromator.

It should be mentioned that it is critical to measure branching ratios from high-lying levels because of the rapidly increasing number of lines.

4. Results and discussion

We have determined absolute oscillator strengths of 116 Fe I lines, 28 of which are suitable for a solar abundance study. The measured lifetimes together with the f-values are listed in Table 1.

Together with our previous results (Bard et al. 1991) the lower levels of the 50 astrophysically interesting lines now cover an energy range from 0.99 to 4.61 eV. The equivalent widths in the solar spectrum are between 7 and 351 mÅ.

We have compared our log(gf) values with other measurements. Thus, mutual deviations of the data sets will be characterized by the mean difference Δ, which is a measure of the shift in the absolute scales. The average deviation in the relative scales will be given by an rms scatter σ.

We have 22 lines in common with the arc measurements of Bridges & Kornblith (1974). The comparison in Fig. 1 shows only a small shift in both scales and a small scatter.

May et al. (1974) were able to measure a large set of faint lines using a Pfund-type arc. They linked their data to the absolute scale of Bridges & Kornblith. The 41 lines in common are sketched in Fig. 2. Although there is no systematic deviation the scatter is large, exceeding 0.1 dex in many cases.

Recently, O'Brian et al. (1991) published a set of more than 1800 lines. They applied nearly the same measuring procedure as we did for both the lifetime and the branching ratio measurments. The 80 lines in common are shown in Fig. 3. The two dashed lines indicate a difference of 25%. Except for a few lines the agreement is within that margin. This is an excellent result in view of the fact that most of the lines are faint and all are pertaining to high excitation potentials.

Nevertheless, for some lines the mutual deviations are by far too large. At present we can only give two possible explanations:

(i) The lines with a large positive difference in the f-values are all in the short wavelength region around 260 nm. The deviations may be explained, e.g., by an erroneous calibration of the spectrum in that region in one of the two experiments. Unfortunately, there are no other literature data that could help resolve this discrepancy.

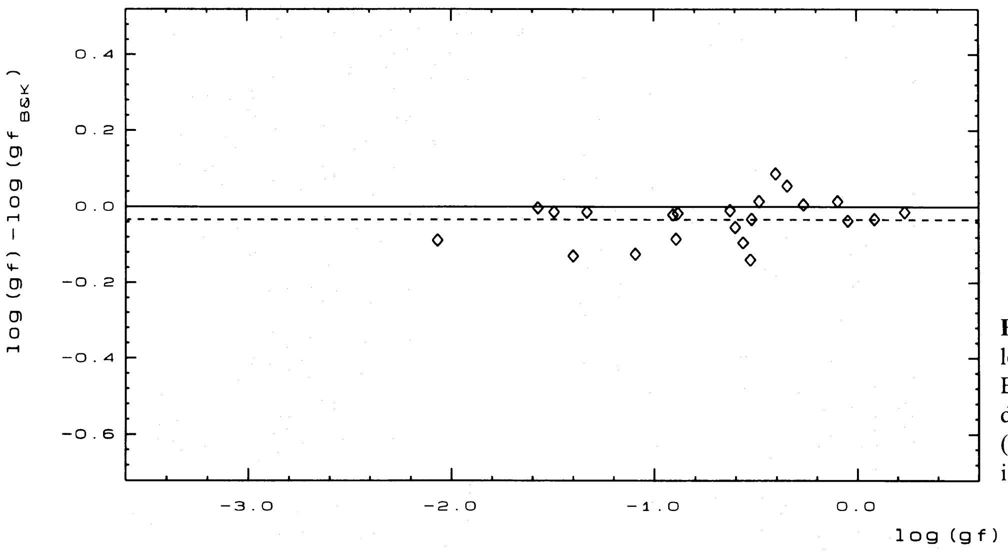

Fig. 1. Comparison of our log(gf) values with the data of Bridges & Kornblith (1974). The difference is $\Delta = -0.034$ dex (dashed line) and the rms scatter is $\sigma = 0.058$ dex

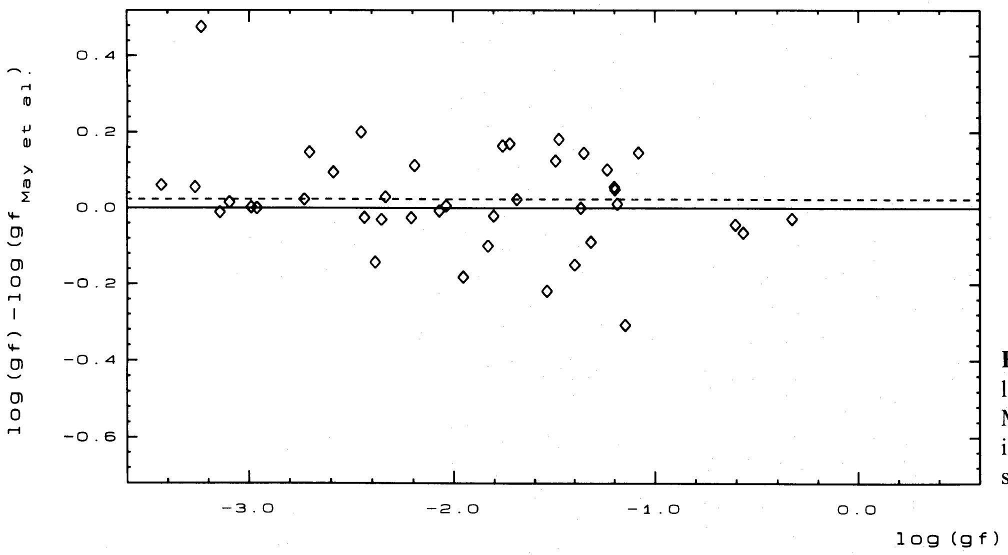

Fig. 2. Comparison of our log(gf) values with the data of May et al. (1974). The difference is only $\Delta = 0.022$ dex whereas the scatter is large with $\sigma = 0.132$ dex

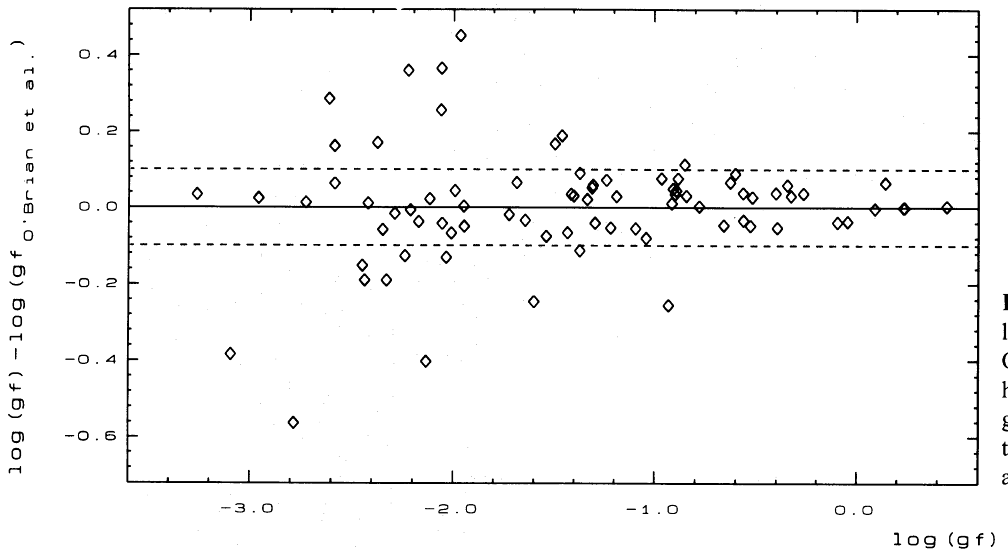

Fig. 3. Comparison of our log(gf) values with the data of O'Brian et al. (1991). The two horizontal lines give a 25% margin. For the 80 lines in common the difference is $\Delta = 0.003$ dex and the scatter is $\sigma = 0.150$ dex

Table 2. Present gf-values (A) compared with data of Blackwell et al. (1984) (B). Lines marked by * are taken from Bard et al. (1991)

λ (nm)	Transition	E_i (eV)	$\log(gf)$ A	$\log(gf)$ B	Δ (A−B)
608.2714	a^5P_1–$z^3P_1^\circ$	2.2227	−3.593*	−3.573	−0.020
615.1619	a^5P_3–$y^5D_2^\circ$	2.1759	−3.265	−3.299	0.034
621.9282	a^5P_2–$y^5D_2^\circ$	2.1979	−2.422	−2.433	0.011
629.7794	a^5P_1–$y^5D_2^\circ$	2.2227	−2.727	−2.740	0.013
648.1872	a^3P_2–$y^5D_2^\circ$	2.2786	−2.960	−2.984	0.024
675.0150	a^3P_1–$z^3P_1^\circ$	2.4242	−2.608*	−2.621	0.013
694.5196	a^3P_1–$z^3P_2^\circ$	2.4242	−2.435*	−2.482	0.047
697.8863	a^3P_0–$z^3P_1^\circ$	2.4844	−2.484*	−2.500	0.016

The lines with large negative differences are all very faint lines. We presume that O'Brian et al. have overestimated these faint lines in their Fourier-transform spectra. A preliminary abundance analysis made by Holweger (1993) shows that the lines at 718 nm (upper level y^3D_2) and at 740 nm (upper level w^3D_1) give anomalous small solar abundances if the f-values of O'Brian et al. are used instead of ours. For the deviation of the other lines there is at present no simple explanation.

Very accurate f-values have been obtained in the furnace absorption experiment by the Oxford group (Blackwell et al. 1984). In our new set we have four lines in common which all belong to the upper level y^5D_2 and which all are suitable for a solar abundance analysis. It should be mentioned that the lines belong to the 2.2 eV anomaly (Blackwell et al. 1984). For a more complete comparison we have listed in Table 2 these four lines with four additional ones from Bard et al. (1991) which have also been used for an abundance determination. As can be seen from the table the agreement between the two small sets of f-values is excellent. That means, discrepancies in the solar iron abundance derived with these f-values cannot be traced back to them. There must be astrophysical reasons for such discrepancies.

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