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# Broadening of lines of Be II, Sr II and Ba II by collisions with hydrogen atoms and the solar abundance of strontium

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**ABSTRACT**

In a previous paper by the present authors the theory of Anstee and O'Mara for the broadening of spectral lines of neutral atoms by collisions with hydrogen atoms was extended to singly ionized atoms. In this paper we apply the method to the resonance and triplet lines of ionized strontium, the infrared triplet of ionized barium, and the resonance lines of ionized beryllium. Analysis of five lines of ionized strontium, previously regarded as too strong for an abundance analysis, and two lines of neutral strontium results in a solar abundance of strontium of $\log(N_{\rm Sr}/N_{\rm H}) + 12 = 2.92 \pm 0.05$, which is entirely consistent with the meteoritic value.

**Key words:** atomic data – line: profiles – Sun: abundances.

## 1 INTRODUCTION

Barklem & O'Mara (1998, hereafter Paper I) extended Anstee & O'Mara's (1991) theory for the broadening of spectral lines of neutral atoms by collisions with hydrogen atoms, to lines of singly ionized atoms. For both neutral and singly ionized atoms the interatomic interaction energy is calculated using Rayleigh–Schrödinger perturbation theory to second order. The second-order term represents the contribution to the interaction resulting from the two-atom system making virtual transitions to intermediate states with the energy debt for each specific transition appearing in the denominator. The expression for the second-order interaction can be greatly simplified if the energy debt, which varies from virtual transition to virtual transition, is replaced by an appropriate fixed debt $E_{\rm p}$, an approximation first suggested by Unsöld (1927). With this approximation the interaction can be expressed simply in terms of the variance in the electrostatic interaction for the two-atom state of interest and $E_{\rm p}$. Because the energy level spacings in neutral atoms are much smaller than the spacings between the ground state and excited states in hydrogen, for all states of neutral atoms, $E_{\rm p}$ can be approximated by a fixed value of $-4/9$ atomic units as suggested by Unsöld (1955). This choice of $E_{\rm p}$ was used by Anstee & O'Mara (1995), Barklem & O'Mara (1997) and Barklem, O'Mara & Ross (1998) to produce tables of line-broadening cross-sections for neutral atoms. Because the energy level spacings for ionized atoms are much greater than for neutrals, $E_{\rm p}$ cannot be approximated by a universal constant value. This was demonstrated by computation of cross-sections for the broadening of resonance lines of Mg II which change by an unacceptable 26 per cent if an $E_{\rm p}$ of $-4/9$ is used rather than our best estimate based on the long-range van der Waals interaction. As a result, unlike the situation for neutral atoms, it is not possible to produce tabulated cross-sections for lines of ionized atoms. However in Paper I it was shown that the theory can be applied to transitions of ions on a line-by-line basis, with $E_{\rm p}$ determined individually for each state.

In Paper I a method for determining the appropriate $E_{\rm p}$ from the long-range van der Waals interaction constant $C_6$ was demonstrated. This method is only appropriate for transitions where the lower and upper states (particularly the upper state) have a set of well determined $f$-values for all important transitions in which the state is involved. The theory was applied to some astrophysically important transitions of Mg II, Ca II and Ba II. In this paper we present results for Be II and Sr II, and add the Ba II 5d–6p triplet.

In astrophysics, beryllium is a very important element for a variety of reasons. The cosmic abundance of beryllium is important in tests of cosmological models (see for example Gilmore, Edvardsson & Nissen 1991). The beryllium abundance also provides constraints on mixing between the photosphere and deeper regions of stars, which is of particular interest in the Sun (see for example Balachandran & Bell 1998).

It was demonstrated by Grevesse (1968) and later pointed out by Chmielewski, Müller & Brault (1975) that 'the determination of the beryllium abundance in the solar atmosphere, based on spectra accessible from the ground, relies essentially on the Be II resonance doublet at 3130 Å', emphasizing the importance of these lines. The general significance of the Be II doublet leads us to consider this transition in this paper even though the doublet is only a very weak feature in stellar spectra.

The resonance and triplet lines of Sr II are extremely important for determination of the abundance of strontium. Goldberg, Müller & Aller (1960) considered these lines to be too strong to be used in abundance determinations; however as the triplet lines are in the infrared their reduced equivalent widths are such that they should

be classified as medium-strong lines rather than strong lines. Lambert & Warner (1968) examined the spectrum of Sr II in the Sun and considered only four of the 10 observed lines to be suitable for analysis. Three of the four lines deemed suitable for analysis are the Sr II 4d–5p triplet in the far-infrared, underlining their importance. They dismissed the resonance lines because of their strength and possible non-local thermodynamic equilibrium (non-LTE) effects in the cores of these lines, which are formed high in the photosphere. Our line-broadening cross-sections for these lines make it possible to derive an abundance from these lines by fitting the damping wings of the lines. Both resonance lines are significantly blended in the wings; however it will be shown later that in spite of this it is still possible to use them in an abundance determination of strontium.

Sr I has no strong lines in the solar spectrum. The resonance line that is the strongest has an equivalent width of only approximately 44 mÅ. In addition very weak lines of Sr I have been used in abundance determinations. Line-broadening cross-sections for Sr I interpolated from the data of Anstee & O'Mara (1995) are presented for later use in an abundance determination from Sr I lines.

Determinations of the solar Ba abundance are based entirely on the lines of Ba II. Results for the resonance lines were presented in Paper I and here we have added results for the 5d–6p triplet. Although the Sr II and Ba II triplets are not particularly strong in the Sun, they do attain substantial strengths in other stars such as Ba- and S-type stars, and this is where the data presented in this paper are expected to be most useful.

## 2 $E_p$ DETERMINATIONS

The method used for calculation of $C_6$ and subsequently $E_p$ values is outlined in Paper I. Values of $C_6$ were calculated for the required states using *f*-values from the sources shown in Table 1. The sources of *f*-values are shown in the order in which preference was given, and the *f*-values used are rated using the scale of A, B, C, D approximately corresponding to 5, 10, 20, 50 per cent average precision of the important *f*-values in the calculation. From these $C_6$ values estimates of $E_p$ were calculated, and these results are summarized in Table 1. Static polarizabilities are also shown for comparison with other work.

For s states (ground states) the contribution to $C_6$ is dominated by the resonance transition, and given the accuracy of these *f*-values the $C_6$ values should be well determined. For the p states examined the most important transitions are those to the nearby s and d states with higher energy. In all cases for s and p states at least half of the *f*-value sum was accounted for, usually approaching unity for s states.

Problems arise in the calculation of $C_6$ for d states, because the *f*-values used for transitions to these states in both cases totalled less than 0.2. The most likely reason for this is that transitions to the continuum and higher-lying *f*-states make a significant contribution to the *f*-value sum. For the d states in Table 1 test calculations using the remainder of the required *f*-value sum at the ionization energy were done, and these alternative values are presented in parentheses. These values are reasonable estimates of the maximum value of $C_6$. It can be seen that the $C_6$ and hence $E_p$ values for these states are quite imprecisely determined. However, the collision broadening of any transition is predominantly determined by the upper state. The negligible effect of these poor determinations on computed cross-sections will be demonstrated in the next section.

## 3 LINE-BROADENING DATA

The data from Table 1, along with appropriate scaled Thomas–Fermi–Dirac wavefunctions (Warner 1968), were used to compute interatomic potential curves for the interaction with hydrogen, which were then used to calculate the line-broadening cross-sections.

Line-broadening cross-sections were calculated for relative perturber velocities $v$, ranging from 3000 to 18 000 m s$^{-1}$. The results for $v = 10\,000$ m s$^{-1}$ are shown in Table 2. The cross-sections are assumed to obey a power law of the form $v^{-\alpha}$, and from regression of the results for various velocities $\alpha$ was found and tabulated.

Results of calculations using the Unsöld value of $E_p = -4/9$ atomic units for both states, and for triplet transitions using the alternative values of $E_p$ for the d state, are also presented. The 'alternative' calculations demonstrate that since the cross-section is mostly dependent on the upper p state, the inaccuracy in the lower d state $E_p$ has little effect on the calculated cross-section. Here the estimated effects of the poorly determined $E_p$ for the lower state were found to be of the order of 4 per cent or less.

A new parameter that measures the sensitivity of the cross-sections to the value of $E_p$ for the upper state is also tabulated. The dependence of the cross-section on the value of $E_p$ has been investigated by Barklem (1998). It was found that the variation of

**Table 1.** Energy denominators for the interaction of selected Be II, Sr II and Ba II states with atomic hydrogen, calculated from dispersion coefficients $C_6$. The radial wavefunction moments $\langle p_2^2 \rangle$ used were calculated using scaled Thomas–Fermi–Dirac wavefunctions (Warner 1968). The accuracy of *f*-values is indicated by the rating A, B, C, D. Values in brackets estimate the likely maximum values for d states (see text).

| Element | State | $C_6$ (atomic units) | *f*-value source[a] (rating) | Polarizability (atomic units) | | $\langle p_2^2 \rangle$ (atomic units) | $E_p$ (atomic units) |
|---|---|---|---|---|---|---|---|
| | | | | This work | Others[b] | | |
| Be II | 2s | 18.1 | WSG (A) | 24.2 | 24.9 (PT) | 6.10 | −0.674 |
| | 2p | 21.9 | WSG (B) | 0.2 | | 6.76 | −0.617 |
| Sr II | 4d | 13.7 (32.8) | GAL (D) | 51.2 | | 10.22 | −1.489(−0.62) |
| | 5s | 51.9 | PBL (A) | 87.5 | 91.5 (PT) | 17.58 | −0.678 |
| | 5p | 104.3 | PBL, GAL, WM (B) | −38.4 | | 29.41 | −0.564 |
| Ba II | 5d | 11.8 (20.6) | DSVD, MW (C) | 27.1 | | 11.79 | −1.998(−1.142) |
| | 6p | 129.8 | DSVD, MW (B) | 38.8 | | 33.21 | −0.512 |

[a] Sources of *f*-values: DSVD = Davidson et al. (1992), GAL = Gallagher (1967), MW = Miles & Wiese (1969), PBL = Pinnington, Berends & Lumsden (1995), WM = Wiese & Martin (1980), WSG = Wiese, Smith & Glennon (1966).
[b] Source of polarizabilities: PT = Patil & Tang (1997).

**Table 2.** Calculated line-broadening cross-sections and $E_p$ dependences. All cross-sections are in atomic units given for a collision speed of $v = 10^4\,\mathrm{m\,s^{-1}}$, with the velocity parameter $\alpha$ given in brackets.

| Element | Transition | This work (theory) | | | Other work[a] (solar) | $E_p$ dependence $\beta$ |
|---|---|---|---|---|---|---|
| | | $E_p$ Table 1 | $E_p = -4/9$ | alternative | | |
| Be II | 2s–2p | 123(0.212) | 132(0.200) | | | −0.032 |
| Sr II | 5s–5p | 262(0.208) | 279(0.198) | | | 0.099 |
| | 4d–5p | 316(0.272) | 320(0.338) | 303(0.337) | | 0.266 |
| Ba II | 5d–6p | 365(0.264) | 357(0.344) | 368(0.241) | 505 ± 168 (HM) | 0.230 |

[a] Sources of other values: HM = Holweger & Müller (1974).

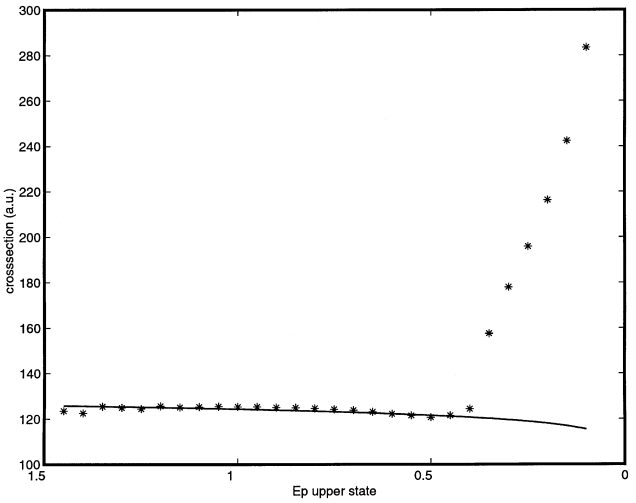


**Figure 1.** Plot showing the dependence of the Be II resonance line cross-section on the $E_p$ chosen for the upper state (stars). The line shows the fit obtained by using $\beta = -0.032$ and the cross-section given in Table 2.

the cross-sections, over the important range of $E_p$ values, can be represented by the simple power-law relationship

$$\sigma \propto |E_p|^{-\beta}. \quad (1)$$

We computed cross-sections for $v = 10\,000\,\mathrm{m\,s^{-1}}$ for values of $E_p$ for the upper state ranging between −0.4 and −1. The lower state $E_p$ was set at the value in Table 1. We then determined the value of $\beta$ by regression.

For every transition of ionized atoms we have considered, we find that the cross-section increases very rapidly with $E_p$ when $E_p$ is greater than −0.4. This was demonstrated in Paper I, and is shown here in Fig. 1 for the resonance lines of Be II where the cross-section is almost constant for $E_p$ in the range −1.5 to −0.4 and then rises rapidly. As the $E_p$ values in Table 1 are all less than −0.4 a weak dependence of the computed cross-sections on $E_p$ is to be expected.

The results in Table 2 show that, in all cases, the broadening has a very weak dependence on $E_p$ in the relevant range, although it is somewhat stronger for d–p transitions where for these infrared lines the cross-sections depend more strongly on the broadening of the lower state than for the s–p transitions considered. For the Be II resonance lines Fig. 1 shows that, over the relevant range, the cross-section is almost independent of $E_p$ leading to a negative value of $\beta$ in the regression. These results underline the appropriateness of the Unsöld (1927) approximation in this work, where we replace the variable energy debt in the second-order perturbation expression by a fixed energy debt allowing the use of completeness to evaluate the infinite sum over intermediate states of the two-atom system.

Inclusion of the parameter $\beta$ not only indicates the sensitivity of the computed cross-sections to the choice of $E_p$ but also allows the cross-sections to be easily rescaled in the event of more accurate values of $C_6$ and hence $E_p$ becoming available. The velocity parameter $\alpha$ also changes with $E_p$. However such changes are too small to affect line profile calculations in cool stars significantly.

### 3.1 Empirical determinations

Holweger & Müller (1974) find that for the abundance determined from strong lines of Ba II to match that found from weak lines, a broadening enhancement factor of about 3.0 ± 1.0 must be used over the value found with the van der Waals interaction. In Table 2 this empirical linewidth has been rescaled to the meteoritic abundance given by Grevesse, Noels & Sauval (1996) and expressed as a cross-section. Their result agrees, at the lower end of the range of uncertainty, with our computed value. However the uncertainty is very large in this empirical determination.

## 4 APPLICATION TO THE SOLAR SPECTRUM

We now apply the data for Sr I and Sr II to the solar spectrum, as a means of both testing the line-broadening cross-sections and examining the solar abundance of strontium.

Strong lines with well-developed and unblended damping wings can be used to confirm our line-broadening calculations. The solar abundance of the element is derived by fitting synthetic damping wings of such lines to the observed solar spectrum. If the solar abundance so derived is in good agreement with the meteoritic abundance then one can conclude that the theoretical cross-sections are satisfactory on the assumption that the solar and meteoritic abundances are the same. However, none of the lines of Sr II considered are sufficiently strong and unblended to be considered ideal. The only lines of suitable strength in the solar spectrum are the resonance lines of ionized strontium; however these are affected by a large number of blending lines. The triplet lines of Sr II do not have well-developed damping wings in the solar spectrum as they have equivalent widths less than 150 mÅ. As they are infrared lines their reduced equivalent widths (which are a better measure of the strength of the lines) indicate that any abundance derived from the equivalent widths will be very sensitive to non-thermal Doppler broadening in the solar atmosphere.

Stark broadening data for these lines are not available but generally Stark broadening is smaller for lines of ionized atoms than for neutral atoms. In addition reference to energy level data for Sr II indicates that for the states of interest there are no nearby perturbing states of opposite parity, so Stark broadening for these lines should be negligible in comparison with broadening by

**Table 3.** Atomic data for lines used in spectral synthesis. The columns in order are: element, wavelength, excitation potential, log *gf* and its source, the radiative damping width, the broadening cross-section in atomic units, the velocity parameter, and the approximate equivalent width of the line, and the derived solar abundance.

| El. | λ (Å) | E.P. (eV) | log *gf* | Source | log $\gamma_{\rm rad}$ (rad $s^{-1}$) | $\sigma$ (atomic units) | $\alpha$ | E.W. (mÅ) | $\log N/N_{\rm H}+12$ This work |
|---|---|---|---|---|---|---|---|---|---|
| Sr I | 4607.338 | 0.0 | 0.283 ± 0.02 | (Migdalek & Baylis 1987) | 8.02 | 404 | 0.257 | 44 | 2.82 |
| Sr I | 7070.078 | 1.85 | −0.150 ± 0.03 | (Gruzdev 1967) | 7.65 | 973 | 0.253 | 1.5 | 2.96 |
| Sr II | 4215.533 | 0.0 | −0.154 ± 0.02 | (Pinnington et al. 1995) | 8.18 | 262 | 0.208 | 233 | 2.92 |
| Sr II | 4077.714 | 0.0 | 0.158 ± 0.02 | (Pinnington et al. 1995) | 8.18 | 262 | 0.208 | 428 | 2.92 |
| Sr II | 10327.314 | 1.83 | −0.240 ± 0.09 | (Gallagher 1967) | 8.18 | 316 | 0.272 | 145 | 2.92 |
| Sr II | 10914.877 | 1.80 | −0.474 ± 0.08 | (Gallagher 1967) | 8.14 | 316 | 0.272 | 133 | 2.88 |
| Sr II | 10036.658 | 1.80 | −1.194 ± 0.08 | (Gallagher 1967)[a] | 8.18 | 316 | 0.272 | 68 | 2.90 |

[a] The uncertainty in this *f*-value in the original paper appears to be overstated by a factor of 10 and has been corrected.

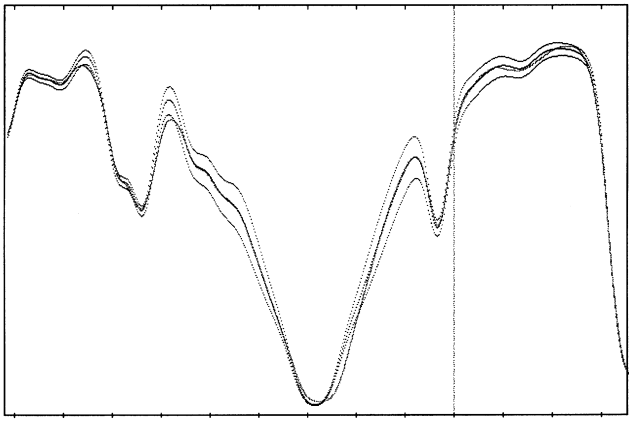

**Figure 2.** Synthesis of a portion of the spectrum containing the 4077-Å resonance line of Sr II. Wavelength markers are at 4078 Å and at every 0.1 Å on either side. The scaled spectral intensity is zero at the bottom and unity at the top of the diagram. The lighter line shows the observed spectrum. Synthetic spectra are displayed for assumed strontium abundances of 2.82, 2.92 (which provides the best fit to the observed spectrum) and 3.02 to indicate the quality of the abundance determination.

collisions with hydrogen atoms. Consequently Stark broadening was neglected in our spectrum synthesis of these lines.

### 4.1 Spectrum synthesis

We use the SYN program of Ross (1999) and disc centre solar spectra from Delbouille, Neven & Roland (1973) and Brault & Testermann (1972). The program can accept non–LTE departure coefficients but as none were available LTE was assumed. We used the model solar atmosphere of Holweger & Müller (1974) with a macroturbulence of 1.6 km $s^{-1}$ and a microturbulence of 0.85 km $s^{-1}$ determined by Blackwell et al. (1987) from disc centre spectra of Ti I and Fe I lines. The data for each line synthesized is shown in Table 3.

We find that for most lines the spectra of Delbouille et al. (1973) and Brault & Testermann (1972) are in very good agreement. However for the very weak lines of Sr I the spectrum of Brault & Testermann (1972) appears superior when viewed at very high magnification; consequently this spectrum has been used throughout our analysis.

### 4.2 The Sr II resonance lines

The stronger of the two resonance lines of Sr II at 4077 Å has a red wing that is relatively unblended in the inner part except for a single line of ionized dysprosium. To synthesize this spectral region, data were extracted from VALD, the Vienna Atomic Line Database (Kupka et al. 1999). The new broadening data were substituted along with the transition probability determined by Pinnington et al. (1995), and the radiative damping constant that we have computed.

The data for the Dy II line resulted in a line that was significantly too deep, and hence the *f*-value was adjusted empirically to obtain a line with approximately the central depth of the observed line; however this adjustment has no effect on the derived abundance. Data for other lines were similarly adjusted to match the observations.

Fig. 2 compares the observed spectrum with the synthetic spectrum. The asymmetry in the observed core of the line is considered to be of similar origin to that seen in the lines of Ca II and discussed by Shine & Linsky (1974). Fig. 2 shows the synthesis using abundances of 2.82, 2.92 and 3.02 indicating the sensitivity of the computed profile to the assumed abundance. An abundance of 2.97, adopted by Grevesse et al. (1996) following a recent determination by Gratton & Sneden (1994), is clearly ruled out.

The Sr II resonance line at 4215.533 Å is severely blended with a strong Fe I line at 4215.425 Å as well as with numerous other lines in both wings. However by including the Fe I line with an *f*-value of −1.76, a line-broadening cross-section from tabulated data (Anstee & O'Mara 1995) and an abundance of 7.51 it was found that a small portion of the Sr II line between 4215.59 and 4215.64 Å, which contributes only about 30 mÅ to the equivalent width of the line, could be used leading to an abundance of 2.92. Owing to the small portion of spectrum that is usable this derived abundance cannot be given a high weight.

The abundance derived from the resonance lines is in excellent agreement with the meteoritic value 2.92 ± 0.02 adopted by Grevesse et al. (1996) and, on the assumption that the solar and meteoritic abundances are identical, supports the computed line-broadening cross-section.

### 4.3 The infrared Sr II triplet

Although these lines are only of medium strength in the Sun, making their equivalent widths sensitive to non-thermal Doppler broadening, the line wings can be used where collisional broadening by hydrogen dominates. Using the computed broadening data and the turbulence parameters specified above, the abundances derived from the 10036-, 10327- and 10914-Å lines are shown in

Table 3. The wings of the lines contribute less than half of their equivalent width and in addition the derived abundance is susceptible to placement of the continuum. The mean abundance is 2.90 but with a high level of uncertainty as the wings of these lines are not sufficiently well developed for a good determination. To within the rather large uncertainty in fitting the synthetic spectrum to the observed spectrum and the uncertainty in the *f*-values the derived abundances are consistent with the meteoritic value and in support of the theoretical line-broadening cross-sections employed.

### 4.4 Sr I lines

In an abundance determination of strontium Gratton & Sneden (1994) use both Sr I and Sr II lines. Their analysis based on Sr I lines uses three lines, the resonance line at 4607 Å, which we find has an equivalent width of 44 mÅ at disc centre, and two very weak lines. The weakest line at 6791 Å they estimate to have an equivalent width of only 0.23 mÅ. Close examination of this line on the disc centre spectrum of Brault & Testermann (1972) indicates that it is somewhat stronger than this and is blended with numerous other lines. An attempt to synthesize a portion of the spectrum containing this line was unsuccessful and consequently this line is unsuitable for an abundance determination.

The line at 7070 Å though also very weak appears as a relatively clean line when the disc centre spectrum of Brault & Testermann (1972) is scaled up by a factor of 60. Hauge (1972) has shown that the theoretical $\log gf$ value for this line obtained by Gruzdev (1967) is midway between two empirical values, suggesting an uncertainty of $\pm 0.03$. A section of spectrum containing this line is shown in Fig. 3. Significantly lines of Mn and Fe which blend only very slightly with this line can be fitted with abundances consistent with their meteoritic values leading to some confidence in the quality of the synthesis. In Fig. 3 the synthetic spectrum is shown for three assumed abundances of strontium, 2.91, 2.96 and 3.01. Because this line is so weak it is completely unsaturated making it very sensitive to changes in the assumed abundance. The derived abundance of 2.96 is independent of all forms of motional and collisional broadening. As the line is formed just above an optical depth of unity in the continuum where the photospheric structure is well determined, the derived abundance should not depend on the particular model atmosphere employed in the analysis.

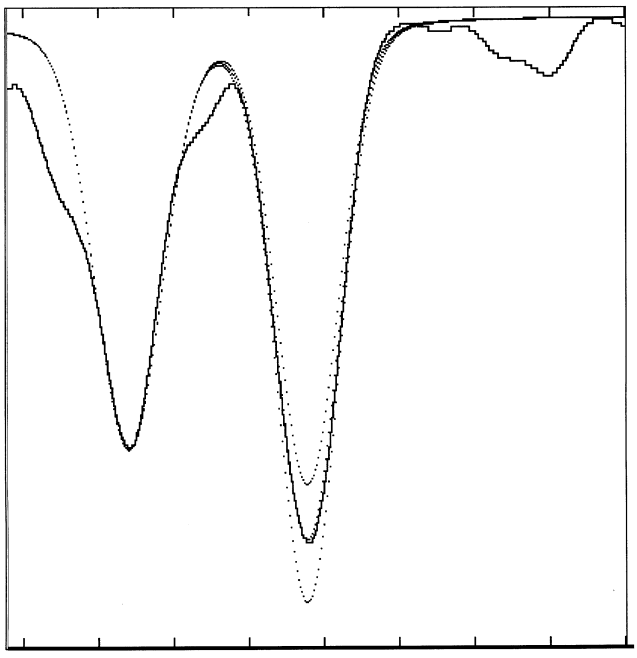

**Figure 3.** Synthesis of a portion of the spectrum containing the 7070.078-Å line of Sr I. Markers are at every 0.1 Å, the leftmost being at 7069.7 Å and the rightmost at 7070.5 Å. The scaled spectral intensity is 0.9833 at the bottom and unity at the top, corresponding to an expansion of the vertical scale by a factor of 60. The observed spectrum is the full line. Synthetic spectra are displayed for assumed strontium abundances of 2.91, 2.96 (which provides the best fit to the observed spectrum) and 3.01 to indicate the quality of the abundance determination. The blending Mn I line at 7069.84 Å indicates a manganese abundance of 5.38, in good agreement with the photospheric abundance 5.39 adopted by Grevesse et al. (1996) but significantly lower than their meteoritic abundance of 5.53.

With an assumed equivalent width of 44 mÅ the abundance derived from the resonance line is 2.82, which is 0.1 dex lower than the meteoritic abundance and the solar abundance derived from other lines. A lower value for the assumed microturbulence leads to a somewhat higher derived abundance but a synthetic profile that does not agree with the observed profile. As the *f*-value for the line is well determined perhaps the most likely explanation for the discrepancy is that the population of the ground state of Sr I is rather lower than the LTE population, but unlike Gratton & Sneden (1994) we do not find that this underpopulation extends to the lower states of weak subordinate lines of Sr I.

In an independent analysis Grevesse & Sauval (private communication) find an equivalent width of $46 \pm 1$ mÅ for this line. If we use an equivalent width of 47 mÅ at the upper limit of their estimate of the equivalent width we obtain an abundance of 2.88, which rises to 2.90 with a small reduction of 0.05 km s$^{-1}$ in the assumed microturbulent velocity. If this higher abundance is adopted then it is in agreement with our adopted value (see Section 4.5) to within the uncertainty in the *f*-value for this line. Although we still believe that this line does lead to a lower abundance, in view of the uncertainty in its equivalent width, its *f*-value and its sensitivity to microturbulence it is perhaps premature to conclude that the lower abundance we obtain is a result of an underpopulation of the ground state of Sr I in the solar photosphere.

### 4.5 The solar abundance of strontium

Fig. 4 plots the abundances derived for each line of Sr I and Sr II against the equivalent width of the line, and demonstrates that apart from the Sr I resonance line the abundances are consistent

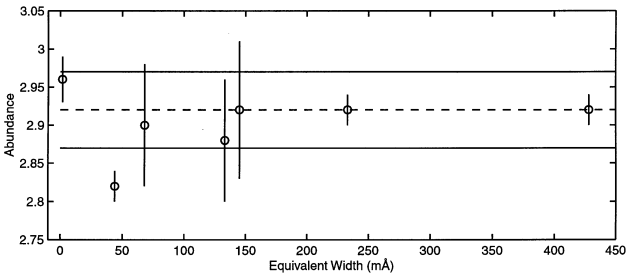


**Figure 4.** Plot showing the variation of the derived abundances for spectral lines of Sr I and Sr II with equivalent width. Error bars include only the error in the *f*-value. The dashed horizontal line shows our best estimate of the solar abundance and the full horizontal lines an estimate of the uncertainty from all sources of error.

across the range of linestrengths. A simple average of the abundances from the weak line of Sr I and the five lines of Sr II leads to $\log(N_{\rm Sr}/N_{\rm H}) + 12 = 2.91$. An estimate of the uncertainty based on the standard deviation is not meaningful because of the small sample size. The result should however be heavily weighted towards the resonance lines of Sr II and the weak line of Sr I. Bearing in mind the uncertainties in the *f*-values for these lines, uncertainties in continuum placement and other factors involved in the synthesis of these lines, our best estimate of the abundance and its associated uncertainty is

$$\log(N_{\rm Sr}/N_{\rm H}) + 12 = 2.92 \pm 0.05. \quad (2)$$

This result is in excellent agreement with the meteoritic abundance $2.92 \pm 0.02$ adopted by Grevesse et al. (1996) and Grevesse & Sauval (1998) and the solar abundance 2.90 determined by Hauge (1972) from very weak lines of neutral strontium. However it is smaller than the solar abundance 2.97 adopted by Grevesse et al. (1996) from the analysis of Gratton & Sneden (1994).

## 5 CONCLUSION

Theoretical line-broadening cross-sections for the resonance lines of Be II and Sr II and the triplet lines of Sr II and Ba II are tabulated. All cross-sections are only weakly dependent on $E_{\rm p}$, especially so for the resonance lines. Along with the cross-sections a new parameter, $\beta$, is provided which indicates the sensitivity of the computed cross-sections to $E_{\rm p}$ and permits the cross-sections to be rescaled in the event of better values of $E_{\rm p}$ becoming available in the future. Comparison of the solar spectrum with synthetic spectra obtained using the meteoritic abundance of strontium and barium supports the cross-sections obtained for the resonance and triplet lines of Sr II and the triplet lines of Ba II. A solar abundance derived from the resonance and triplet lines of Sr II and a single weak line of Sr I is in excellent agreement with the meteoritic abundance. The resonance line of Sr I which has a well determined *f*-value leads to a low abundance of strontium, which indicates that the ground state of Sr I may be underpopulated.

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