THE ASTROPHYSICAL JOURNAL, 248:867–873, 1981 September 1


# OSCILLATOR STRENGTHS FOR Zr I AND Zr II AND A NEW DETERMINATION OF THE SOLAR ABUNDANCE OF ZIRCONIUM

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*Received 1980 December 30; accepted 1981 March 5*

## ABSTRACT

A new determination of the solar abundance of zirconium has been made using equivalent-width data measured on the Jungfraujoch solar atlas together with new oscillator strengths derived from measurements of atomic lifetimes and branching ratios for 34 lines of Zr I and 24 lines of Zr II. Excellent agreement is found between the results derived from Zr I and Zr II lines and also with recent meteoritic results. The mean abundance of zirconium in the Sun is found to be $A_{Zr} = 2.56 \pm 0.05$.

*Subject headings:* Sun: abundances — transition probabilities

## I. INTRODUCTION

The first "modern" value of the abundance of zirconium in the Sun was given by Goldberg, Müller, and Aller (1960). Using Zr I equivalent widths measured on the Utrecht atlas (Minnaert, Mulders, and Houtgast 1940) and Coulomb-approximation $f$-values, they found $A_{Zr} = 2.23$ [where $A_{Zr}$ means $\log (N_{Zr}/N_H) + 12.00$ in the usual scale]. Since the publication of the experimental transition probabilities of Corliss and Bozman (1962; hereafter CB), these data have been used by various authors to derive new solar abundances of zirconium. Aller (1965), using 11 Zr I lines, found $A_{Zr} = 2.65$; Wallerstein (1966), using seven Zr II lines, found $A_{Zr} = 2.2$; Grevesse, Blanquet, and Boury (1968), using both Zr I (15 lines) and Zr II (28 lines), measured on new, high-resolution solar tracings, obtained a large difference between the results derived from Zr I ($A_{Zr} = 3.31$) and Zr II ($A_{Zr} = 2.28$). Recently, Ross and Aller (1976), in a review on the chemical composition of the Sun, adopted a value of $A_{Zr} = 2.75$.

Since their publication in 1962, the experimental $f$-values of CB have been shown to contain significant excitation-dependent, wavelength-dependent, and intensity-dependent errors (see, e.g., Corliss and Tech 1976; Corliss 1967; Bell and Upson 1971). However, these were the only $f$-value data available on zirconium when the above analyses were undertaken.

A new determination of the abundance of zirconium in the Sun is justified by the large scatter of the individual results ($A_{Zr}$ ranging from 2.2 to 3.3) and by the significant discrepancies observed between the values derived from Zr I and Zr II lines. Moreover, two of us (Hannaford and Lowe 1981) have recently developed a method for determining accurate atomic lifetimes in elements such as zirconium, and in this paper we apply the method to a wide range of levels of Zr I and Zr II. The measured lifetimes, when combined with newly measured branching ratios, yield $f$-values which in most cases differ significantly from the CB values. These revised $f$-values are combined with new equivalent-width data measured on the Jungfraujoch solar atlas (Delbouille, Neven, and Roland 1973) to obtain a new value of the solar abundance of zirconium.

## II. ZIRCONIUM TRANSITION PROBABILITIES

### a) *Lifetime Measurements*

Zirconium is a highly refractory element which is difficult to vaporize by conventional thermal means. Until very recently, the only lifetime results were reported by Ramanujam and coworkers (Ramanujam 1977; Andersen, Ramanujam, and Bahr 1978) who used a beam-sputtering excitation technique to study the $z^3G^o_{3-5}$ and $y^5G^o_{4-5}$ levels of Zr I. We have recently reported (Hannaford and Lowe 1981) a new technique which is suitable for determining lifetimes in neutral and singly ionized atoms of a wide range of elements, including highly refractory elements such as zirconium. In this method, an atomic vapor of the required metal is produced by cathodic sputtering in a low-pressure, rare-gas discharge and selectively excited by short optical pulses from a nitrogen-laser pumped dye laser. Measurements are then made of the time decay of the emitted atomic fluorescence. The technique is free from cascading, transit-time and line-blending effects. Our reported lifetimes for the $z^3G^o_{3-5}$ and $y^5G^o_{2-6}$ levels of Zr I suggest that the beam-sputtering results for zirconium are consistently high by factors of 3–4.

We have now extended these lifetime measurements to 34 levels of Zr I and 20 levels of Zr II which include the upper levels of the selected solar lines discussed in § III. The method used is the same as described previously (Hannaford and Lowe 1981). Checks were made to eliminate any shortening of the lifetimes due to collisional depopulation by the rare gas (neon) and possibly length-

ening of the lifetimes due to radiation trapping. The system was tested by determining the lifetimes of eight well-established levels of Ca, Al, Na, Cr, Fe, and U, which span the range from 4 to 200 ns (Hannaford and Lowe 1981). Most of the zirconium levels of astrophysical interest have lifetimes within this range.

The lifetime values ($\tau$) found for the various levels of Zr I and Zr II are summarized in the third columns of Tables 1 and 2. Each value represents, typically, the mean of 10 determinations. The wavelengths shown in these tables are the wavelengths of the solar lines and are not necessarily the same as the laser excitation wavelengths.

### *b) Branching-Ratio Measurements*

The branching ratios for transitions originating from an upper level $j$ can be expressed as

$$R_{ji} = \frac{A_{ji}}{\sum_k A_{jk}} = \frac{I_{ji}\lambda_{ji}}{\sum_k I_{jk}\lambda_{jk}}, \quad (1)$$

where $A_{ji}$ is the transition probability for the $j \rightarrow i$ transition and $I_{ji}$ is the emission intensity in units of energy (per unit time and solid angle). Using this relationship, branching ratios have been determined for the zirconium lines of interest by measuring the relative intensities of the various lines which originate from each relevant upper level. The zirconium light source was a hollow-cathode lamp filled with either krypton or neon. Krypton was useful for enhancing the Zr II spectrum, while neon was sometimes required to avoid interference from krypton gas lines. The lamp was operated at low currents to eliminate any self-absorption of the lines. Most of the intensity measurements were taken on an 0.5 m monochromator at a bandwidth of about 0.1 Å, although for a few of the lines a higher resolution monochromator (3.8 m, bandwidth about 0.02 Å) was required. The spectral response of the combined monochromator-photomultiplier system was determined over the range from 2500 to 9000 Å using calibrated deuterium and quartz-iodine lamps.

TABLE 1

LIFETIME, BRANCHING RATIO, AND OSCILLATOR STRENGTH DATA FOR ZR I LINES

| $\lambda$(Å) | Transition | $\tau$(ns)[a] | $R$[a] | $R_{CB}$[b] | $f$[a] | $f_{CB}$[b] |
|---|---|---|---|---|---|---|
| 3501.333 ..... | $a^3F_3$–$y^5F^o_4$ | 7.0 (2) | 0.049 (3) | 0.074 | 0.017 (1) | 0.010 |
| 3509.331 ..... | $a^3F_3$–$v^3D^o_2$ | 8.6 (2) | 0.73 (2) | 0.75 | 0.112 (4) | 0.079 |
| 3575.765 ..... | $a^3F_3$–$w^3F^o_4$ | 8.1 (3) | 0.44 (3) | 0.49 | 0.13 (1) | 0.076 |
| 3601.198 ..... | $a^3F_4$–$x^3G^o_5$ | 6.6 (2) | 0.92 (2) | 0.91 | 0.33 (1) | 0.22 |
| 3663.698 ..... | $a^3F_4$–$w^3F^o_4$ | 8.1 (3) | 0.46 (3) | 0.42 | 0.115 (8) | 0.052 |
| 3891.383 ..... | $a^3F_4$–$z^1G^o_4$ | 22.5 (1) | 0.88 (3) | 0.87 | 0.089 (5) | 0.051 |
| 4028.93 ..... | $a^3P_2$–$z^1P^o_1$ | 7.6 (2) | 0.20 (1) | 0.18 | 0.038 (2) | 0.022 |
| 4030.049 ..... | $a^5F_1$–$x^5D^o_1$ | 5.8 (2) | 0.34 (2) | 0.37 | 0.145 (9) | 0.090 |
| 4043.608 ..... | $a^3P_2$–$x^3P^o_2$ | 10.2 (5) | 0.36 (2) | 0.38 | 0.086 (6) | 0.056 |
| 4072.696 ..... | $a^5F_4$–$x^5D^o_3$ | 5.8 (2) | 0.68 (2) | 0.66 | 0.23 (1) | 0.14 |
| 4241.706 ..... | $a^5F_3$–$y^5F^o_3$ | 7.1 (2) | 0.52 (2) | 0.51 | 0.20 (1) | 0.09 |
| 4507.100 ..... | $a^3P_1$–$x^3D^o_2$ | 12.8 (2) | 0.30 (3) | 0.29 | 0.12 (1) | 0.06 |
| 4542.234 ..... | $a^1D_2$–$x^3D^o_3$ | 13.0 (3) | 0.30 (2) | 0.28 | 0.099 (5) | 0.038 |
| 4687.805 ..... | $a^5F_5$–$y^5G^o_6$ | 12.0 (5) | 1.00 (1) | 0.996 | 0.33 (1) | 0.089 |
| 4710.077 ..... | $a^5F_4$–$y^5G^o_5$ | 13.3 (3) | 0.85 (2) | 0.83 | 0.26 (1) | 0.078 |
| 4732.323 ..... | $a^1D_2$–$x^1F^o_3$ | 20.7 (5) | 0.29 (2) | 0.24 | 0.065 (5) | 0.020 |
| 4739.454 ..... | $a^5F_3$–$y^5G^o_4$ | 13.1 (3) | 0.73 (2) | 0.74 | 0.24 (1) | 0.067 |
| 4772.310 ..... | $a^5F_2$–$y^5G^o_3$ | 13.3 (3) | 0.61 (2) | 0.52 | 0.22 (1) | 0.054 |
| 4784.94 ..... | $a^5F_4$–$y^3G^o_5$ | 27.6 (6) | 0.23 (2) | 0.13 | 0.036 (3) | 0.0083 |
| 4805.89 ..... | $a^5F_5$–$y^5G^o_4$ | 13.1 (3) | 0.16 (1) | 0.14 | 0.034 (2) | 0.0083 |
| 4809.477 ..... | $a^3G_5$–$u^3F^o_4$ | 11.4 (4) | 0.52 (2) | 0.39 | 0.130 (7) | 0.035 |
| 4815.056 ..... | $a^5F_3$–$y^3G^o_4$ | 21.5 (4) | 0.20 (1) | 0.094 | 0.042 (2) | 0.0086 |
| 4815.637 ..... | $a^5F_1$–$y^5G^o_2$ | 12.3 (3) | 0.67 (2) | 0.52 | 0.31 (1) | 0.067 |
| 4828.06 ..... | $a^5F_2$–$y^3G^o_3$ | 16.2 (3) | 0.15 (1) | 0.076 | 0.046 (3) | 0.011 |
| 5046.55 ..... | $b^3F_4$–$w^3G^o_5$ | 7.8 (3) | 0.21 (2) | 0.17 | 0.13 (1) | 0.054 |
| 5385.128 ..... | $a^3P_2$–$y^1D^o_2$ | 73 (2) | 0.66 (2) | 0.63 | 0.039 (2) | 0.0092 |
| 5885.629 ..... | $a^3F_3$–$z^3F^o_4$ | 520 (30) | 0.084 (5) | 0.106 | 0.0011 (1) | 0.00064 |
| 6127.46 ..... | $a^3F_4$–$z^3F^o_4$ | 520 (30) | 0.88 (2) | 0.86 | 0.0096 (6) | 0.0044 |
| 6134.57 ..... | $a^3F_2$–$z^3F^o_2$ | 500 (10) | 0.94 (3) | 0.94 | 0.0106 (5) | 0.0026 |
| 6140.46 ..... | $a^3P_2$–$z^3P^o_2$ | 280 (5) | 0.38 (2) | 0.36 | 0.0077 (4) | 0.0026 |
| 6143.183 ..... | $a^3F_3$–$z^3F^o_3$ | 410 (15) | 0.81 (2) | 0.73 | 0.0113 (5) | 0.00030 |
| 6313.03 ..... | $a^3G_5$–$z^3H^o_6$ | 36.5 (1.0) | 0.87 (4) | 0.78 | 0.17 (1) | 0.038 |
| 6445.72 ..... | $a^1G_4$–$y^3F^o_3$ | 205 (10) | 0.69 (5) | 0.56 | 0.016 (1) | 0.0026 |
| 6990.84 ..... | $a^5F_2$–$z^5D^o_2$ | 163 (10) | 0.27 (2) | 0.31 | 0.012 (1) | 0.0052 |
| 7097.76 ..... | $a^5F_4$–$z^5D^o_3$ | 148 (5) | 0.75 (2) | 0.76 | 0.030 (1) | 0.012 |
| 7102.89 ..... | $a^5F_4$–$z^5D^o_2$ | 163 (10) | 0.62 (3) | 0.58 | 0.021 (2) | 0.0073 |
| 7819.35 ..... | $a^3D_3$–$w^3D^o_3$ | 41.5 (1.0) | 0.27 (2) | 0.37 | 0.060 (5) | 0.039 |
| 7849.38 ..... | $a^5F_4$–$z^5F^o_5$ | 220 (7) | 0.108 (5) | 0.098 | 0.0056 (3) | 0.0019 |

[a] This work.

[b] Corliss and Bozman 1962.

NOTE.—Figures in parentheses represent uncertainty in last figure(s).

TABLE 2

LIFETIME, BRANCHING RATIO, AND OSCILLATOR STRENGTH DATA FOR Zr II LINES

| λ(Å) | Transition | τ(ns)[a] | R[a] | $R_{CB}$[b] | f[a] | $f_{CB}$[b] |
|---|---|---|---|---|---|---|
| 3432.415 ..... | $a^4P_{1/2}-y^4D^o_{3/2}$ | 3.9 (2) | 0.097 (5) | 0.125 | 0.088 (6) | 0.24 |
| 3454.591 ..... | $a^4P_{1/2}-y^4F^o_{3/2}$ | 4.9 (2) | 0.031 (2) | ... | 0.023 (2) | ... |
| 3458.940 ..... | $a^4P_{3/2}-y^4D^o_{3/2}$ | 3.9 (2) | 0.162 (2) | 0.19 | 0.075 (5) | 0.18 |
| 3479.025 ..... | $a^2D_{3/2}-y^2D^o_{3/2}$ | 8.6 (3) | 0.24 (2) | 0.17 | 0.051 (5) | 0.055 |
| 3479.393 ..... | $a^2F_{5/2}-z^2G^o_{7/2}$ | 4.8 (3) | 0.49 (2) | 0.49 | 0.25 (2) | 0.38 |
| 3499.572 ..... | $b^4F_{7/2}-z^4F^o_{9/2}$ | 4.55 (20) | 0.038 (2) | 0.047 | 0.019 (1) | 0.023 |
| 3505.671 ..... | $a^4F_{9/2}-z^4G^o_{9/2}$ | 5.75 (20) | 0.136 (6) | 0.143 | 0.044 (2) | 0.043 |
| 3549.525 ..... | $b^4P_{5/2}-z^4P^o_{3/2}$ | 10.6 (3) | 0.56 (2) | 0.64 | 0.067 (3) | 0.12 |
| 3551.957 ..... | $a^4F_{7/2}-z^4G^o_{7/2}$ | 6.0 (3) | 0.19 (1) | 0.28 | 0.061 (4) | 0.093 |
| 3588.325 ..... | $b^4F_{7/2}-z^2D^o_{5/2}$ | 8.4 (4) | 0.054 (3) | 0.074 | 0.0093 (7) | 0.018 |
| 3607.379 ..... | $b^4P_{5/2}-z^4S^o_{3/2}$ | 4.2 (3) | 0.124 (6) | 0.138 | 0.038 (3) | 0.14 |
| 3630.027 ..... | $b^4F_{5/2}-z^2D^o_{3/2}$ | 7.2 (3) | 0.070 (4) | 0.082 | 0.013 (1) | 0.02 |
| 3671.276 ..... | $a^2F_{5/2}-y^2D^o_{3/2}$ | 8.6 (3) | 0.27 (2) | 0.32 | 0.042 (3) | 0.075 |
| 3714.787 ..... | $a^2D_{3/2}-z^2D^o_{5/2}$ | 8.4 (4) | 0.079 (5) | 0.066 | 0.029 (2) | 0.035 |
| 3796.496 ..... | $a^2G_{9/2}-z^2G^o_{7/2}$ | 4.8 (3) | 0.041 (2) | 0.045 | 0.015 (1) | 0.025 |
| 3836.769 ..... | $a^2D_{5/2}-z^2F^o_{7/2}$ | 8.2 (4) | 0.41 (2) | 0.39 | 0.15 (1) | 0.14 |
| 4034.091 ..... | $a^2F_{7/2}-z^4F^o_{7/2}$ | 4.65 (20) | 0.0067 (5) | 0.0058 | 0.0035 (3) | 0.0033 |
| 4050.329 ..... | $a^2F_{5/2}-z^2D^o_{3/2}$ | 7.2 (3) | 0.073 (5) | 0.058 | 0.017 (1) | 0.018 |
| 4071.093 ..... | $a^4P_{5/2}-z^4D^o_{5/2}$ | 7.0 (2) | 0.0118 (6) | ... | 0.0042 (2) | ... |
| 4085.731 ..... | $a^4P_{1/2}-z^4D^o_{1/2}$ | 6.7 (2) | 0.033 (2) | ... | 0.0124 (8) | ... |
| 4149.202 ..... | $a^2F_{7/2}-z^2F^o_{7/2}$ | 8.2 (4) | 0.37 (2) | 0.29 | 0.116 (8) | 0.093 |
| 4161.208 ..... | $a^2F_{5/2}-z^4F^o_{3/2}$ | 6.3 (3) | 0.116 (6) | 0.112 | 0.032 (2) | 0.033 |
| 4208.985 ..... | $a^2F_{5/2}-z^2F^o_{5/2}$ | 8.0 (2) | 0.17 (1) | 0.16 | 0.058 (4) | 0.048 |
| 4258.049 ..... | $a^2D_{5/2}-z^4G^o_{5/2}$ | 7.1 (3) | 0.032 (2) | 0.032 | 0.012 (1) | 0.0093 |
| 4264.925 ..... | $b^2D_{3/2}-y^4F^o_{5/2}$ | 4.6 (2) | 0.011 (2) | ... | 0.010 (2) | ... |
| 4317.321 ..... | $a^2F_{5/2}-z^4G^o_{7/2}$ | 6.0 (3) | 0.011 (1) | 0.009 | 0.0071 (7) | 0.0055 |
| 4443.001 ..... | $a^2H_{9/2}-z^2G^o_{7/2}$ | 4.8 (3) | 0.095 (5) | 0.042 | 0.047 (4) | 0.033 |
| 4445.849 ..... | $b^2D_{3/2}-z^2P^o_{3/2}$ | 3.9 (3) | 0.015 (2) | ... | 0.011 (2) | ... |
| 4496.974 ..... | $a^2F_{5/2}-z^4G^o_{5/2}$ | 7.1 (3) | 0.061 (4) | 0.038 | 0.026 (2) | 0.013 |
| 4613.921 ..... | $a^2G_{7/2}-z^2F^o_{5/2}$ | 8.0 (2) | 0.013 (2) | ... | 0.0038 (6) | ... |
| 5112.279 ..... | $b^2D_{3/2}-y^2D^o_{3/2}$ | 8.6 (3) | 0.14 (1) | 0.038 | 0.064 (5) | 0.025 |

[a] This work.
[b] Corliss and Bozman 1962.
NOTE.—Figures in parentheses represent uncertainty in last figure(s).

The branching ratios ($R$) found for the various Zr I and Zr II lines are listed in the fourth columns of Tables 1 and 2, together with values derived from the transition probabilities of CB. The $R$-values derived from CB tend to be more reliable than the individual $f_{CB}$-values since $R$ depends only on the relative transition probabilities for transitions from a given level and also is independent of any excitation-dependent errors. However, significant discrepancies do exist, particularly for lines with small $R$-values where intensity-dependent errors may be important.

### c) *Oscillator Strengths*

The $f$-values were derived from our lifetime and branching-ratio results using the expression

$$f = (mc/8\pi^2e^2)(g_j\lambda^2 R/g_i\tau) . \quad (2)$$

The quantities $g_i$ and $g_j$ are the statistical weights of the lower and upper level respectively, and $m$ is the electronic mass. The values obtained are summarized in the final columns of Tables 1 and 2, together with the results of CB. For Zr I lines, our $f$-values are higher than the $f_{CB}$-values by factors of up to 6, whereas for Zr II lines our values tend to be lower. This difference in the ratio $f/f_{CB}$ between Zr I and Zr II provides an explanation for much of the discrepancy previously observed between the solar abundance values derived from Zr I and Zr II lines.

Allen's (1976) "solar" $f$-values for Zr II, which have been used recently in stellar analyses, are lower than ours by factors ranging from about 2 to 4 for the lines common to both studies.

## III. SELECTION OF THE SOLAR LINES

The lines identified as due to zirconium by Moore, Minnaert, and Houtgast (1966) in their table of identifications of the solar spectrum have been carefully examined on the very high resolution (resolving power $\sim 10^6$) and low noise (signal-to-noise ratio of $\sim 2000$) tracings of the Jungfraujoch solar atlas of Delbouille, Neven, and Roland (1973; until now, only spectra between 3500 Å and 8000 Å have been published). This search led us initially to retain 38 Zr I and 31 Zr II lines for which accurate $f$-values are now available (see Tables 1 and 2). Equivalent widths ($W_\lambda$) for these lines have been measured independently by E. B. and N. G. and the results examined and discussed after making the measurements. Uncertainties have been assigned to each line on the basis of the agreement between the two sets of measurements and the appearance of the lines in the solar spectrum.

It is important in the final analysis to exclude lines which are influenced by blending since these lead to systematically high abundance values. An examination of the frequency distribution of the abundances derived from the various lines (see § IV) shows that the distributions for both Zr I and Zr II exhibit an extended tail on the high-abundance side. Thus, in the final analysis, we have excluded two Zr I lines and seven Zr II lines for which the abundance values exceed the mean by more than 3 standard deviations. A further two Zr I lines (3663.698 and 5885.629 Å), which have been identified as probable blends by Moore, Minnaert, and Houtgast (1966) and for which the abundance values exceed the mean by more than 2 standard deviations, have also been excluded. The 34 Zr I and 24 Zr II lines we have retained and their measured equivalent widths are listed in the upper sections of Tables 3 and 4. The rejected lines are shown in the lower sections of these tables.

The differences between our equivalent widths and those reported by Moore, Minnaert, and Houtgast (1966) can be explained by the better quality of the solar tracings we have used. Allen (1976) also gives equivalent widths for a few of the Zr II lines we have measured, and some of his results are 10–20% higher than ours. The difference may be a result of the simplified rule used to derive his equivalent widths. The present list of lines differs some-

TABLE 3

DATA AND RESULTS FOR ZR I

| $\lambda$ (Å)[a] | $E_{low}$ (eV) | $W_\lambda$ (mÅ)[b] | log $gf$[c] | $A_{Zr}$[d] | Weight[c] |
|---|---|---|---|---|---|
| 3509.331 | 0.07 | 6.5 (5) | −0.11 | 2.45 | 2 |
| 3601.198 | 0.15 | 13 (1) | 0.47 | 2.29 | 2 |
| 3891.383 | 0.15 | 17 (2) | −0.10 | 2.89 | 1 |
| 4028.93 | 0.52 | 0.6 (1) | −0.72 | 2.28 | 1 |
| 4030.049[e] | 0.60 | 2.6 (4) | −0.36 | 2.65 | 1 |
| 4043.608 | 0.52 | 5.8 (9) | −0.37 | 2.95 | 1 |
| 4072.696 | 0.69 | 5.7 (4) | 0.31 | 2.42 | 2 |
| 4241.706[e] | 0.65 | 3.7 (3) | 0.14 | 2.33 | 2 |
| 4507.100 | 0.54 | 3.6 (2) | −0.43 | 2.76 | 2 |
| 4542.234 | 0.63 | 4.6 (1) | −0.31 | 2.83 | 4 |
| 4687.805 | 0.73 | 10.0 (5) | 0.55 | 2.43 | 3 |
| 4710.077 | 0.69 | 10.5 (8) | 0.37 | 2.59 | 2 |
| 4732.323 | 0.63 | 2.5 (4) | −0.49 | 2.72 | 1 |
| 4739.454 | 0.65 | 5.5 (3) | 0.23 | 2.38 | 3 |
| 4772.310 | 0.62 | 5.3 (3) | 0.04 | 2.52 | 3 |
| 4784.94 | 0.69 | 1.6 (1) | −0.49 | 2.57 | 2 |
| 4805.89 | 0.69 | 1.5 (1) | −0.42 | 2.47 | 2 |
| 4809.477[f] | 1.58 | 1.6 (1) | 0.16 | 2.77 | 2 |
| 4815.056 | 0.65 | 2.0 (2) | −0.53 | 2.67 | 2 |
| 4815.637 | 0.60 | 3.0 (1) | −0.03 | 2.30 | 4 |
| 4828.06 | 0.62 | 1.9 (3) | −0.64 | 2.73 | 1 |
| 5046.55[f] | 1.53 | 0.50 (4) | 0.06 | 2.29 | 2 |
| 5385.128 | 0.52 | 1.8 (1) | −0.71 | 2.63 | 4 |
| 6127.46 | 0.15 | 2.1 (3) | −1.06 | 2.63 | 1 |
| 6134.57 | 0.00 | 1.9 (3) | −1.28 | 2.66 | 1 |
| 6140.46 | 0.52 | 0.73 (5) | −1.41 | 2.88 | 2 |
| 6143.183 | 0.07 | 2.1 (2) | −1.10 | 2.59 | 1 |
| 6313.03 | 1.58 | 1.1 (2) | 0.27 | 2.40 | 1 |
| 6445.72 | 1.00 | 0.94 (5) | −0.83 | 2.86 | 2 |
| 6990.84[g] | 0.62 | 0.50 (4) | −1.22 | 2.57 | 2 |
| 7097.76 | 0.69 | 2.1 (3) | −0.57 | 2.61 | 1 |
| 7102.89 | 0.65 | 0.65 (4) | −0.84 | 2.33 | 3 |
| 7819.35[g] | 1.82 | 0.65 (9) | −0.38 | 2.96 | 1 |
| 7849.38 | 0.69 | 1.0 (2) | −1.30 | 2.97 | 1 |
| 3501.333[f] | 0.07 | 7 (1) | −0.93 | 3.31 | 1 |
| 3575.765 | 0.07 | 33 (2) | −0.03 | 3.37 | 2 |
| 3663.698[e] | 0.15 | 25 (2) | 0.01 | 3.10 | 2 |
| 5885.629[e] | 0.07 | 0.50 (3) | −2.12 | 3.00 | 2 |

[a] From Moore, Minnaert, and Houtgast 1966.
[b] Measured on Jungfraujoch spectra (Delbouille, Neven, and Roland 1973).
[c] See text.
[d] Calculated with Holweger and Müller 1974 model.
[e] Identified as Zr I-(probable blend of Zr I with an unnamed line) by Moore, Minnaert, and Houtgast.
[f] Identified as Zr I? by Moore, Minnaert, and Houtgast.
[g] New identification proposed.
NOTE.—The upper part of the table lists the lines retained in the final analysis.

TABLE 4

DATA AND RESULTS FOR ZR II

| λ (Å)[a] | $E_{low}$ (eV) | $W_\lambda$ (mÅ)[b] | log $gf$[c] | $A_{Zr}$[d] | Weight[e] |
|---|---|---|---|---|---|
| 3432.415 | 0.93 | 21 (3) | −0.75 | 2.69 | 1 |
| 3454.591 | 0.93 | 10.0 (5) | −1.34 | 2.83 | 2 |
| 3458.940 | 0.96 | 16 (2) | −0.52 | 2.31 | 1 |
| 3479.025 | 0.53 | 28 (1) | −0.69 | 2.47 | 2 |
| 3479.393 | 0.71 | 51 (3) | 0.17 | 2.53 | 2 |
| 3499.572 | 0.41 | 24 (1) | −0.81 | 2.33 | 2 |
| 3505.671 | 0.16 | 51 (3) | −0.36 | 2.57 | 3 |
| 3549.525 | 1.24 | 16 (1) | −0.40 | 2.43 | 2 |
| 3551.957 | 0.09 | 58 (4) | −0.31 | 2.67 | 2 |
| 3588.325 | 0.41 | 27 (4) | −1.13 | 2.73 | 1 |
| 3607.379 | 1.24 | 13 (1) | −0.64 | 2.54 | 2 |
| 3671.276 | 0.71 | 32 (2) | −0.60 | 2.53 | 2 |
| 3714.787 | 0.53 | 30 (2) | −0.93 | 2.64 | 2 |
| 3796.496 | 1.01 | 15 (2) | −0.83 | 2.48 | 1 |
| 3836.769 | 0.56 | 47 (7) | −0.06 | 2.28 | 1 |
| 4034.091 | 0.80 | 6.5 (1.0) | −1.55 | 2.53 | 1 |
| 4050.329 | 0.71 | 23.8 (6) | −1.00 | 2.61 | 2 |
| 4085.731 | 0.93 | 5.4 (4) | −1.61 | 2.62 | 2 |
| 4208.985 | 0.71 | 43 (2) | −0.46 | 2.58 | 3 |
| 4258.049 | 0.56 | 26 (1) | −1.13 | 2.65 | 2 |
| 4317.321[e] | 0.71 | 12.0 (9) | −1.38 | 2.55 | 2 |
| 4443.001 | 1.49 | 20 (2) | −0.33 | 2.51 | 2 |
| 4496.974 | 0.71 | 36 (3) | −0.81 | 2.71 | 2 |
| 5112.279 | 1.66 | 8.3 (2) | −0.59 | 2.40 | 2 |
| 3630.027 | 0.36 | 38 (6) | −1.11 | 3.01 | 1 |
| 4071.093[f] | 1.00 | 21 (2) | −1.60 | 3.38 | 2 |
| 4149.202 | 0.80 | 75 (10) | −0.03 | 3.10 | 1 |
| 4161.208 | 0.71 | 58 (10) | −0.72 | 3.29 | 1 |
| 4264.925 | 1.66 | 15.0 (4) | −1.41 | 3.59 | 1 |
| 4445.849[f] | 1.66 | 8.3 (2) | −1.35 | 3.21 | 1 |
| 4613.921 | 0.97 | 29.1 (7) | −1.52 | 3.46 | 1 |

[a] From Moore, Minnaert, and Houtgast 1966.
[b] Measured on Jungfraujoch spectra (Delbouille, Neven, and Roland 1973).
[c] See text.
[d] Calculated with Holweger and Müller 1974 model.
[e] Identified as Zr II-(probable blend of Zr II with an unnamed line) by Moore, Minnaert, and Houtgast.
[f] Identified as Zr II? by Moore, Minnaert, and Houtgast.
NOTE.—The upper part of the table lists the lines retained in the final analysis.

what from the lines analyzed by Grevesse, Blanquet, and Boury (1968), who measured the equivalent width using an earlier unpublished version of the Jungfraujoch atlas. For the 22 lines in common with our present analysis, the equivalent widths agree to within 5%.

## IV. SOLAR LINE ANALYSIS

The solar abundance of zirconium has been derived for each line using the data given in Tables 3 and 4. We used the method of direct integration of the line profiles, assuming local thermodynamic equilibrium (see, e.g., Aller 1963). In deriving the abundance for each line, successive iterations were performed in order to match the calculated and observed equivalent widths. As most of the lines used are faint, even very faint, the present analysis is independent of line-broadening parameters.

Two commonly used solar photospheric models were first retained: the model by Holweger and Müller (1974; hereafter HOLMU) and the model by Vernazza, Avrett, and Loeser (1976; hereafter VERNAL). Temperatures in the two models are in agreement for optical depths between log $\tau_0 = -0.20$ and $-0.70$. Moving to higher layers, the HOLMU temperatures become higher than the VERNAL ones: $\Delta T = 105$ K at log $\tau_0 = -1.00$, $\Delta T = 150$ K at log $\tau_0 = -1.50$, $\Delta T = 190$ K at log $\tau_0 = -2.00$, and $\Delta T = 260$ K at log $\tau_0 = -2.50$. The results for Zr II are practically insensitive to the model used, in contrast with the situation for Zr I, where $A_{Zr}$(HOLMU) − $A_{Zr}$(VERNAL) varies from 0.15 to 0.22. Thus, it is important to be able to make a choice between these two models.

Lambert (1978) and Lambert and Luck (1978) have checked the validity of different model solar atmospheres, comparing predicted and observed continuum intensities and limb-darkening observations. These comparisons led them to adopt the HOLMU model. Ayres (1978) also showed that the VERNAL temperature distribution needs to be increased. Allen (as quoted by Lambert, by Ayres, and also by Avrett 1977) derived a new temperature distribution from unpublished limb-darkening ob-

servations in the infrared. His model has higher temperatures than those of VERNAL for $\log \tau_0 < -0.70$ and is not very different from the HOLMU model in the higher layers. Furthermore, the minimum temperatures around $\log \tau_0 = -3.5$ derived by Rast, Kneubühl, and Müller (1978) from far-infrared measurements and by Samain (1979) from ultraviolet observations are also about 300 K higher than the minimum temperature adopted in the VERNAL model. Consideration of all of these results leads us to choose the HOLMU model in preference to the VERNAL one. An *a posteriori* argument in favor of this choice is given in § V: it leads to excellent agreement between the abundances deduced from the Zr I and Zr II lines.

We have adopted a microturbulent velocity, $\xi = 0.8$ km s$^{-1}$ (isotropic and independent of depth), in agreement with the results of Blackwell and Shallis (1979). The sensitivity of our results to the microturbulence is discussed in § V.

## V. SOLAR RESULTS AND DISCUSSION

Our detailed results are given in Table 3 (Zr I) and Table 4 (Zr II). Each $A_{Zr}$-value is assigned a weighting factor from 1 to 4, as estimated from the combined effect of the uncertainties in $f$ and $W_\lambda$. Weight 4 is assigned to lines with $\delta A_{Zr} \leq 0.06$, weight 3 to lines with $0.06 < \delta A_{Zr} \leq 0.08$, weight 2 to lines with $0.08 < \delta A_{Zr} \leq 0.13$ and weight 1 to lines with $0.13 < \delta A_{Zr} < 0.4$. The weighted means of all the results are:

$$A_{Zr} = 2.57 \pm 0.07 \quad \text{for Zr I(34 lines)},$$

$$A_{Zr} = 2.56 \pm 0.05 \quad \text{for Zr II(24 lines)}.$$

The quoted errors represent twice the standard deviation of the mean.

Using the VERNAL model, one would obtain $A_{Zr} = 2.40$ (Zr I) and $A_{Zr} = 2.53$ (Zr II). The stronger dependence of the Zr I result on the model may be explained as follows. In the layers where the Zr I and Zr II lines are formed (around $\log \tau_0 = -1.2$ to $-1.3$ for Zr I, using the contribution functions defined following Cowley 1970, and around $\log \tau_0 = -1.0$ for Zr II), the ratio $N_{Zr\,II}/N_{Zr\,I}$ is rather large, ranging from 60 to 30 (HOLMU) and from 100 to 50 (VERNAL). This ratio is rather sensitive to the model through its dependence on temperature and electron pressure. For such large degrees of ionization, the combined Boltzmann and Saha equations show that the abundance values derived from Zr II lines are practically independent of $N_{Zr\,II}/N_{Zr\,I}$ (the dependence on temperature is essentially through the Boltzmann equation only), in contrast to the situation for Zr I where the derived abundance values depend on temperature through both the Boltzmann and Saha equations. The Zr II lines are thus much less sensitive to temperature than the Zr I lines and are better abundance indicators.

To check the dependence of our results on the microturbulent velocity, $\xi$, we varied this parameter from 0.5 to 1.0 km s$^{-1}$. For Zr I, all lines are faint, and the results are in practice independent of $\xi$. For Zr II, one obtains for $\xi = 0.5$ km s$^{-1}$, $A_{Zr} = 2.61$, and for $\xi = 1.0$ km s$^{-1}$, $A_{Zr} = 2.52$, which are to be compared with $A_{Zr} = 2.56$ for $\xi = 0.8$ km s$^{-1}$ and with $A_{Zr} = 2.57$, deduced from the Zr I lines.

The excellent agreement between the Zr I and Zr II results is a further argument in favor of the HOLMU model (Zr II results are insensitive to the model) and of the microturbulence, $\xi = 0.8$ km s$^{-1}$, that we have adopted (Zr I results are independent of $\xi$).

The mean solar abundance of zirconium deduced from this study is

$$A_{Zr} = 2.56 \pm 0.05 .$$

The accepted value for the meteoritic abundance of zirconium has been substantially reduced during the last few years (see, e.g., Ganapathy, Papia, and Grossman 1976 and Shima 1979). From recent works, we adopt the value $10.5 \pm 1.5$ zirconium atoms per $10^6$ silicon atoms. Normalized to the solar scale (Biémont, Grevesse, and Huber 1978), this leads to

$$A_{Zr}(\text{meteorites}) = 2.55 \pm 0.06 .$$

Our solar result is in excellent agreement with this value.

We wish to express our gratitude to D. S. Gough and P. L. Larkins for their assistance with the branching-ratio measurements and to E. Anders and J. P. Meyer for discussions concerning the meteoritic abundance of zirconium. One of us (E. B.) has been supported by the Belgian "Fonds National de la Recherche Scientifique."

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