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# Atomic data for absorption lines from the ground level at wavelengths greater than 228 Å*

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**Abstract.** We list wavelengths, statistical weigths and oscillator strengths for 2249 spectral lines arising from the ground states of atoms and ions. The compilation covers all wavelengths longward of the He II Lyman limit at 227.838 Å and all the ion states of all elements from hydrogen to bismuth ($Z = 83$) for which reliable data are known. We assign experimental wavelengths to 1086 lines which have oscillator strengths calculated in the Opacity Project, and add 1163 lines which have critically evaluated oscillator strengths from previous compilations. The presented data are to be used for quasar absorption spectra interpretation. We use solar abundances to calculate the expected relative strengths of all absorption lines, and list separately the strongest lines above 228 Å expected in QSO absorption systems, many of which are listed here for the first time. The great majority of strong lines expected in quasar spectra are at $\lambda < 912$ Å. We also list the strongest absorption lines of various ions without wavelength restriction.

**Key words:** atomic data – quasars: absorption lines

## 1. Introduction

Accurate atomic data are essential in various fields of astrophysics, from solar physics to quasar spectroscopy. Of particular interest are absorption line spectra of high redshift QSOs, which are the main source of information on the chemical composition and physical state of gas in early epoch galaxies and thereby on the cosmic evolution of interstellar and intergalactic matter. Reliable vacuum wavelengths and oscillator strengths are needed to identify absorption lines in QSO spectra and to derive parameters such as column densities, temperatures and velocity structure.

In this paper we present new data on atomic absorption lines arising from the ground state. The particle and radiation densities in the interstellar medium and in the gas which produces quasar absorption systems are usually sufficiently low that nearly all atoms and ions are in their ground states, and consequently the absorption lines arising in such gas are nearly all transitions from the ground (zero energy) level. At higher densities or in more intense radiation absorption may arise from excited fine structure levels (e.g. C II* 1335.6672, 1335.7077 – see Bahcall & Wolf 1968; Morton 1991, hereafter M91), and from upper levels (e.g. the Balmer lines in stellar spectra), but we will not consider such lines.

M91 presented a compilation of atomic data for the lines involving the ground level and excited fine structure levels of the ground term. He included allowed and intersystem absorption lines of all ion stages of all elements from hydrogen to germanium ($Z = 32$) with wavelengths longward of the hydrogen Lyman limit at 911.75 Å. Since then there have been three developments. We now have quasar spectra which extend down below 300 Å, we have much improved signal to noise in both the satellite UV and from the ground, and there are improved atomic data.

Satellites now routinely observe wavelengths well below 912 Å. The Hubble Space Telescope (HST) is measuring spectra down to 1150 Å, which corresponds to rest frame wavelengths $300 \lesssim \lambda_0 \lesssim 900$ Å for high $z$ QSOs, and both the existing Hopkins Ultraviolet Telescope and the proposed Far-Ultraviolet Spectroscopic Explorer mission will observe in the $912 \lesssim \lambda \lesssim 1200$ Å range, covering rest frame wavelengths down to approximately 200 Å. Using HST, Reimers et al. (1992) identify many absorption lines with wavelengths $\lambda_0 \gtrsim 350$ Å in the spectrum of the bright quasar HS1700+6416, and many other spectra are being obtained.

The HIRES spectrograph on the W.M. Keck telescope is now producing spectra of quasars with SNR $= 30 - 80$ per 0.01 Å in the rest frame which are sensitive to absorption lines with rest frame equivalent widths of $W_{\rm rest} \leq 1$ mÅ, two orders of magnitude weaker than the limit in typical samples of absorption lines, and one order of magnitude better than the previous record.

In the meantime, a large international collaboration known as the Opacity Project (OP) has produced a complete set of accurate atomic data for all stages of ionization of astrophysically abundant elements: $1 \leq Z \leq 14$ and $Z = 16, 18, 20, 26$, where $Z$ is atomic number (Seaton et al. 1992). In particular, the OP data include oscillator strengths for all optically allowed transitions between states with $n \leq 10$ and $l \leq 4$, where $n$ and $l$ are the active-electron principal and orbital angular momentum respectively. The OP data exclude intersystem (spin-forbidden) transitions. The OP calculations are based on high level meth-

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*All tables are also available in electronic form: see the Editorial in A&AS 1994, Vol. 103, No. 1

ods such as the R-matrix method (Burke et al. 1971) and the new asymptotic techniques developed by Seaton (1985). Extensive comparisons of the OP data with experiment and theory (Seaton et al. 1992; Mendoza 1992) have confirmed the high accuracy of the OP calculations.

Here we present the data needed to interpret absorption lines with wavelengths $\lambda \geq 227.838$ Å, the He II Lyman limit. We give vacuum wavelengths, statistical weights and oscillator strengths for absorption lines from the ground level. In a separate table we list the strongest absorption lines of various ions without wavelength restriction. The data are virtually complete for all stages of ionization of all elements from hydrogen to nickel ($Z = 28$). In addition, the compilation includes parameters for lines with reliably known oscillator strengths for heavier elements up to bismuth ($Z = 83$).

We do not apply strict criteria to the line selection; rather we include all ground level absorption lines which have experimental wavelengths and critically evaluated oscillator strengths, and we use solar abundances to calculate the expected relative strengths of these absorption lines.

In section 2 of this paper we discuss the sources of data and compare OP oscillator strengths with ones from earlier compilations. In section 3 we discuss the expected relative strengths of absorption lines arising from the ground level. The strongest lines above 228 Å expected in QSO spectra are listed in a table, and in a separate table we list the strongest lines above 228 Å without experimental wavelengths. In section 4 we explain the four main atomic data tables, the last two of which are long.

We present six tables.

1. Strong lines above 228 Å expected in quasar absorption systems;
2. Strongest lines above 228 Å without experimental wavelengths;
3. Atomic weights and solar-system abundances;
4. Ionization thresholds and strongest lines of atoms and ions;
5. Resonance absorption lines above 228 Å ordered by element;
6. Resonance absorption lines above 228 Å ordered by wavelength.

In keeping with modern practice for quasars, all wavelengths in this paper are vacuum values. Some older papers use air values above 2000 Å. The standard conversion formula is Eq. (1) of Morton & Smith (1973), or Eq. (3) of M91.

## 2. Data

### *2.1. Opacity Project data and experimental wavelengths*

The OP data available through the TOPbase 0.6 database (Cunto et al. 1993) include $gf$-values for all multiplets of optically allowed transitions between states with $n \leq 10$ and $l \leq 4$ for all ionization states of elements with atomic number $1 \leq Z \leq 14$, $Z = 16$, 18, 20 and for $N \leq 24$ for $Z = 26$ (iron), where $N$ is the number of electrons. The total number of multiplets exceeds $10^6$, but only 6018 involve the ground terms. In the OP calculations relativistic effects are neglected, and therefore $LS$-coupling is assumed throughout. The $f$-values of individual lines in multiplets based on $LS$-coupling can be easily calculated (see, e.g., Allen 1973). The 6018 multiplets include 9569 lines originating from the ground (zero energy) level, and of these 2189 lines have the theoretical wavelengths above 200 Å. The OP theoretical wavelengths are accurate to a few angstroms, which is not good enough for spectroscopy, so they must be replaced by experimental wavelengths and wavelengths calculated from experimental energy levels which are usually good to $\sim 0.001$ Å.

Main sources of experimental wavelengths are Kelly (1987, hereafter K87; lines below 2000 Å) and M91 (resonance lines above 911.75 Å). We have also used compilations of experimental energy levels (Bashkin & Stoner 1975, 1978; Sugar & Corliss 1985) to calculate accurate wavelengths. Finally, we have undertaken an extensive literature search (complete to December 1993) to find new and improved experimental wavelengths in original papers. We attempted to assign accurate wavelengths to all 2189 OP lines which originate from the ground level with theoretical wavelengths $\geq 200$ Å. We obtained accurate wavelengths longward of 227.838 Å for 1086 of these lines: 230 from M91, 540 from K87, 174 with wavelengths calculated from experimental energy levels, and 142 lines from new original papers.

Some of the remaining 1103 lines were rejected because they had accurate wavelengths below 227.838 Å, but for most we could not locate accurate wavelengths and we have only the approximate theoretical wavelengths. Fortunately, most such lines are weak higher order lines of spectroscopic series, but the few exceptions which are strong will be specified in Table 2 below.

We subsequently used the experimental wavelengths to improve the $f$-values calculated by the OP. The OP calculations give line strength $S$ and transition energy $E$, where $S$ is given by an integral over the atomic wave functions and does not involve $E$. Then $gf$-values are calculated from $S$ and $E$ since $gf = \mathrm{const} \times S \times E$ (or $gf = \mathrm{const} \times S/\lambda$). The OP used their theoretical values of $E$ to calculate $gf$-values. To improve the $gf$-values we now use the more accurate experimental wavelengths instead of the theoretical $E$ values. We recalculated the OP $f$-values as: $f_{\mathrm{improved}} = f_{\mathrm{OP}} \times (\lambda_{\mathrm{OP}}/\lambda_{\mathrm{exp}})$.

### *2.2. Additional data from Morton (1991)*

We obtained $f$-values of lines from M91 in addition to those from the OP. M91 includes oscillator strengths for 907 ground level lines at $\lambda \geq 911.75$ Å. Of these, 564 lines belong to species not covered by the OP (including 155 lines of Fe I and Fe II), 239 lines are in common with the OP, and 104 lines are non-$LS$-type or higher order ($n > 10$) lines of the OP species. Above 911.75 Å, we include 67 lines with OP $f$-values and experimental wavelengths which are not covered by M91. All are of species with $E < 13.6$ eV (65 neutrals and 2 lines of Ca II).

Figure 1 shows a comparison of the improved OP $f$-values with those from M91 for the 239 lines in common. The agreement is generally good, with some exceptions. The largest discrepancies are for twelve lines of S I (M91 source: unpublished semi-empirical data by Kurucz) and for three lines of Ca I which do not have reliable identifications: OP, M91 and Bashkin & Stoner (1978) all disagree. Note that M91 erroneously gave $f = 0.5459$ for C I 1157.1857 Å; it should be $f = 0.00055$.

### *2.3. Data from Fuhr & Wiese (1991) and the NBS data*

Additional lines and $f$-values were obtained from Fuhr & Wiese (1991, hereafter FW) and from the U.S. National Bureau of Standards (NBS) publications (Wiese et al. 1966, 1969; Martin et al. 1988; Fuhr et al. 1988).

FW include data for about 8300 selected lines of all elements up to Bi ($Z = 83$) for which reliable data are available. We selected from this compilation the data for the ground level lines, and converted transition probabilities $A_{ik}$ into oscillator strengths $f_{ik}$ in accordance with the standard formula:

$$g_i f_{ik} = 1.499 \times 10^{-8} \lambda^2 g_k A_{ik}, \quad (1)$$

where $\lambda$ is in Å and $A_{ik}$ is in $10^8$ s$^{-1}$. In most cases FW give wavelengths to two or sometimes only one decimal place, whereas other compilations give more. We replaced the FW wavelengths with those from K87, Bashkin & Stoner (1975, 1978), Sugar & Corliss (1985) for elements with $Z \leq 36$, and from Moore (1950, 1952a,b, 1958, 1959, 1962) for the heavier elements ($Z \geq 37$, 8% of the data). The latter will not always be better than the FW values, because in some cases Moore's compilations overestimate accuracy giving 3 decimal places, and in other cases FW underestimate accuracy, giving values to only 0.1 – 0.01 Å. Note that FW give the air wavelengths of lines above 2000 Å.

We supplemented the FW data with those from previous NBS compilations of atomic transition probabilities (Wiese et al. 1966, 1969; Martin et al. 1988; Fuhr et al. 1988). We replaced wavelengths given by Wiese et al. (1966, 1969) with improved values from the more recent compilations of experimental wavelengths described above.

In total we give $f$-values from FW and NBS compilations for 746 lines. Of these, 400 lines belong to species not covered by the OP, 251 lines are in common with the OP, and 95 lines are non-$LS$-type or higher order ($n > 10$) lines of the OP species. FW and NBS tables include only 36 lines with $\lambda >$ 911.75 Å from the ground level of elements with $Z \leq 32$ which were omitted by M91. Seventeen of them are transitions to high orders ($n \geq 14$) of the hydrogen Lyman series, and the others are weak lines of Be I, B I, Ne VI, Cu I, Zn I, Ga I, and Ge I. Only 3 of these 36 lines are covered by the OP: Be I 1661.478 and 1491.765 Å, and B I 2089.559 Å.

Figure 2 shows a comparison of the improved OP $f$-values with those from the NBS compilations for 251 lines in common. The agreement with the recent compilations (FW, Martin et al. 1988, Fuhr et al. 1988) is generally good, but some values from earlier compilations (Wiese et al. 1966, 1969) have large discrepancies.

In the whole, we include data on oscillator strengths of 2249 lines from three main sources: 1086 lines from the OP, 668 additional lines from M91, and 495 additional lines from FW and NBS publications (Wiese et al. 1966, 1969; Martin et al. 1988; Fuhr et al. 1988). We excluded from our compilation the OP data for all lines of Ne I, Na II, Ar I, and also for three lines of Si I, since the OP assumption of $LS$-coupling is not satisfactory for them. For these lines we list $f$-values from previous compilations only. For 490 OP lines which have been included in the previous compilations, we list older $f$-values along with the new OP values. The accuracy of OP data can deteriorate for neutral and singly ionized species. For one line (Be I 1491.765 Å), the OP $f$-value is obviously too small. This line is clearly seen experimentally (see K87 and references therein), and its intensity fits smoothly in a sequence of other lines in the spectroscopic series of $1s^2\,2s^2 - 1s^2\,2s\,np$ transitions. In the meantime, the OP $f$-value for this particular line does not at all fit the sequence of other oscillator strengths for this spectroscopic series. In most cases, the OP data are more accurate than other theoretical data from earlier compilations, but experimental $f$-values from older sources may be preferred over the OP calculations. We do not include in the present compilation new oscillator strengths from recent papers. Some of them may improve the listed $f$-values, and some others belong to new lines which are important for astrophysics (see, e.g., Cardelli et al. 1993). In a subsequent paper, we will compile all available oscillator strengths of the ground level lines, and will evaluate their accuracy.

## 3. Expected strengths of absorption lines

In total, we have collected oscillator strengths and experimental wavelengths for 2249 absorption lines. For all these lines, we calculated the expected width (strength) parameter

$$P = \log(\lambda f) + \log(N/N_{\rm H}) + 12.00, \quad (2)$$

where $N/N_{\rm H}$ is the abundance of the element relative to hydrogen, and $\lambda$ is in Å. We used the solar-system abundances of Anders & Grevesse (1989), which we list in Table 3. Provided the element is entirely in the ion of the line in question, and there is no line saturation,

$$W_{\rm rest} = 8.85 \times 10^{P-33} N_{\rm H} \lambda \quad (3)$$

where $W_{\rm rest}$ is the (rest frame) line equivalent width in Å, $\lambda$ is in Å and $N_{\rm H}$ is in cm$^{-2}$. A line with $W_{\rm rest} = 1$ mÅ at $\lambda = 1000$ Å would be produced by a transition with $P = 4.15$ in the quasar damped Lyman-$\alpha$ system with the largest known $N_{\rm H} = 8 \times 10^{21}$ cm$^{-2}$. If the line is saturated, or if some of the element is in different ions, or if the metal abundances are below solar, then the absorption line will be weaker than given by Eq. (3), so we do not expect to see many lines with $P \leq 4$.

Figure 3 gives a graphical presentation of the relative strengths of the 2198 metal lines arising from the ground level which have wavelengths from 228 to 8000 Å. We also show C I 841 Å which is very strong (but without an experimental wavelength), but we omit all H and He lines. The wavelength scale is logarithmic, because most lines are in the far UV. All strengths have been normalized to that of the strongest metal line which is O V 629.730 Å with $P = 11.44$, so we plot $D = 10^{P-11.44}$, where $D$ is proportional to $W_{\rm rest}/\lambda$ for unsaturated lines, from gas with solar abundances and assuming that the element is in one ionization state. Most lines are too weak to show up on this plot. We identify all lines with $D \geq 0.05$ ($P \geq 10.14$) on the plot, but if two lines in a doublet both have $D \geq 0.05$, both are shown but the wavelength is given for only the stronger line.

Morton et al. (1988, hereafter MYJ) presented a list of strong lines above 912 Å suitable for an initial search of QSO absorption systems (Table 4 of MYJ). They included lines with $P \geq 9.49$ longward of the hydrogen Lyman-$\alpha$, and $P \geq 9.98$ shortward. They omitted all species with ionization potentials $E < 13.6$ eV, since low ionization species are not common in QSO absorption spectra.

In Table 1 we extend the MYJ list of strong lines expected in quasar absorption spectra down to 228 Å. For species with $E \geq 13.6$ eV, we include all lines with $P \geq 9.49$ above 1215.67 Å and $P \geq 9.98$ below 1215.67 Å. In addition, Table 1 includes strong lines of ions with $P$ less than these thresholds, which do not have other stronger lines. Above 912 Å, we added the doublet S VI 933.378/944.523 Å with $P = 9.89/9.59$. We also added the strongest ($P > 10.5$) lines above 912 Å for neutrals with $E < 13.6$ eV: MgI 2852.9642 Å, FeI 2484.0205 Å, and four lines of CI. Other differences with Table 4 of MYJ at $\lambda \geq 912$ Å are:

(i) Multiplets of NI at 1200 Å and OI at 989 Å were not resolved in MYJ;

(ii) MYJ did not mark OI at 1025.76 Å (almost the same wavelength as HI Lyman-$\beta$ at 1025.7233 Å), although it had $P = 10.19$ from their data.

All other lines above 912 Å in Table 1 are the same as in MYJ. Small discrepancies in $P$-values are mostly due to differences in the chemical abundances used by MYJ and by us. To save space, we list only the five strongest lines of HI, HeI, and HeII. Table 1 includes 53 lines above 912 Å and 98 lines below 912 Å. Note that 27 lines below 912 Å were not included in the previous compilations of atomic transition probabilities and oscillator strengths (FW, Fuhr et al. 1988, Wiese et al. 1966, 1969). We have divided Table 1 into six wavelength segments, separated by gaps at the Lyman-$\alpha$ and Lyman limit wavelengths of HI, HeI and HeII. Many of the lines are doublets. We note that work on quasar absorption lines has mostly been restricted to lines in the largest wavelength segment, and that most of the other lines have not yet been observed. Theoretical far-UV absorption spectra show that these lines should be seen in HST spectra of quasars (e.g., Verner et al. 1994).

We have also calculated the strength parameters $P$ for all lines from the ground level with OP $f$-values which do not have experimental wavelengths. Table 2 includes lines with $P \geq 9.00$ for the strongest line from the ground level of a multiplet. Their theoretical wavelengths (good to a few angstroms) are all above 228 Å. For all these species there are no experimental data at the corresponding wavelength ranges, except for CaV, where data are available (see K87 and references therein) but line identifications are ambiguous, and no lines were classified in the $3s^2 3p^4(^3\mathrm{P}) - 3p^3(^4\mathrm{S}^\circ)4s(^3\mathrm{D}^\circ)$ multiplet.

## 4. Tables of atomic data

The bulk of this paper contains tables of atomic data, which are explained below.

### *4.1. Table 3. Atomic weights and solar-system abundances*

Table 3 gives standard atomic weights (scaled to the abundance of $^{12}$C equal to 12.00) recommended by the commission on Atomic Weights and Isotopic Abundances (Holden & Martin 1983), and the solar-system abundances $\log(N/N_{\mathrm{H}}) + 12.00$ from Anders & Grevesse (1989). The abundances are meteoritic for all elements except H, C, N, O (solar photosphere abundances) and He, Ne, Ar, Kr, Xe (solar wind abundances). For completeness, we reproduce all elements with known abundances. These abundances were used in the calculation of the line strength $P$ values.

### *4.2. Table 4. Ionization thresholds and strongest lines of atoms and ions*

Table 4 gives the basic atomic data for all ionization states of atoms. The columns are:

| | | |
|---|---|---|
| Species | | |
| $Z$ | – | atomic number |
| $N$ | – | number of electrons |
| Configuration | – | ground state electronic configuration. Only the five outer shells are indicated |
| $E$, eV | – | ionization potential, from K87 at $Z \leq 36$ and from Moore (1970) at $Z \geq 37$. The values which are based on extrapolation rather than observation are enclosed in square brackets |

The last 5 columns list parameters of the strongest resonance line of the species:

| | |
|---|---|
| $\lambda$, Å | – vacuum wavelength |
| $g_i$ | – lower (ground) level statistical weight |
| $g_k$ | – upper level statistical weight |
| $f_{ik}$ | – oscillator strength |
| $P$ | – expected strength parameter from Eq. (2) |

Since the OP data include $f$-values for all allowed transitions between states with $n < 11$ and $l < 5$, we can choose the strongest line for any ion of elements with $Z \leq 14$, $Z = 16$, 18, 20, 26. Wavelengths for lines below 228 Å have been taken from K87. Some lines of elements covered by the OP which have no experimental wavelengths but must be the strongest ones for given ions, are enclosed in square brackets. The parameters of the strongest lines for FeI and FeII have been taken from M91.

For elements not covered by the OP, the strongest lines have been selected from ones with known oscillator strengths and experimental wavelengths. The oscillator strengths have been taken from M91, FW, Martin et al. (1988), Fuhr et al. (1988), Cheng et al. (1979; multiconfiguration Dirac-Fock calculations for Li-like through F-like isoelectronic sequences), Drake (1979; calculations for He-like isoelectronic sequence), and Wiese et al. (1969), in this order of priority. A few species of the elements not covered by the OP are not included in the table, because we lack oscillator strengths for these ions (ScVI, TiVII, etc.).

Ionization thresholds can be used to determine which ions are likely to be present, while the strongest lines and their $P$ values can be used to determine which ions of which elements might be detectable. In many damped Lyman-$\alpha$ systems ZnII $\lambda$2026.136 with $P = 7.67$ has been detected with $W_{\mathrm{rest}} \simeq 0.1$ Å (e.g., Pettini & Hunstead 1990), so with HIRES on the Keck telescope we should see low ionization lines at $\lambda \geq 900$ Å with $P \geq 5.7$ in such absorption systems. These will include lines from elements such as B, F, P, Cl, Ar, Sc, Ti, V, Co, Ni, Cu, Ga and Ge, which all have low ionization ions with $E \geq 13.6$ eV and lines at $\lambda \geq 900$Å. For systems with exceptionally high $N_{\mathrm{H}}$ and high metal abundances, and with high signal to noise ratios we may also see lines with $4 \leq P \leq 5.7$ from elements such as Br, Sr, Y, Cd, Xe, Ba, Yb and Pb.

### *4.3. Table 5. Resonance absorption lines above 228 Å ordered by element*

This table is sorted by element, ionization state (starting with the most electrons), multiplet (starting with the ground level lines with the largest wavelength), wavelength (decreasing wavelength within the multiplet). The lines of some multiplets overlap in wavelength with lines of other multiplets, so lines are not all in order of decreasing wavelength. Only the ground level lines are included. The columns are as follows:

| | | |
|---|---|---|
| Species | | |
| Transition | – | lines with uncertain classification are marked by : |
| Multiplet | | |
| $\lambda$, Å) | – | vacuum wavelength |
| $g_i$ | – | lower (ground) level statistical weight |
| $g_k$ | – | upper level statistical weight |
| $f_{ik}$ | – | improved OP oscillator strength |
| $f'_{ik}$ | – | oscillator strength from other compilations taken in the following order of priority: M91, FW, Martin et al. (1988), Fuhr et al. (1988) and Wiese et al. (1966, 1969) |
| $P$ | – | expected strength parameter from Eq. (2). For the calculation of this parameter in the cases where both $f_{ik}$ and $f'_{ik}$ are available, we used $f_{ik}$. The only exception is 1491.765 Å line of BeI, where $f'_{ik}$ was used |
| Ref | – | reference to experimental wavelength (numbers are explained at the end of the table) |

If the experimental wavelengths are known for the stronger ground level lines of a multiplet but are not known for weaker ground level lines of this multiplet, estimated values of the latter wavelengths are given in square brackets.

### *4.4. Table 6. Resonance absorption lines above 228 Å ordered by wavelength*

This table is sorted by wavelength. Only the ground level lines with known oscillator strengths and experimental wavelengths are included. The entries are the following:

| | | |
|---|---|---|
| $\lambda$, Å | – | vacuum wavelength |
| Species | | |
| $g_i$ | – | lower (ground) level statistical weight |
| $g_k$ | – | upper level statistical weight |
| $f_{ik}$ | – | oscillator strength |
| $P$ | – | expected strength parameter from Eq. (2) |

Oscillator strengths have been taken from the $f_{ik}$ entry of Table 5, if possible, (i.e., the improved OP $f$-values); otherwise, from the $f'_{ik}$ entry of Table 5 which come from the other compilations described above. The only exception is the 1491.765 Å line of BeI, where $f'_{ik}$ was used.

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## Figure captions

**Fig. 1.** The Opacity Project (OP) oscillator strengths, $f$, against the oscillator strengths from Morton (1991), $f'$. Triangles: 12 lines of S I (Morton's source: unpublished semi-empirical data by Kurucz). Circles: Ca I lines with different classifications in the OP and Morton (1991).

**Fig. 2.** The Opacity Project (OP) oscillator strengths, $f$, against the oscillator strengths from other compilations, $f'$, for the lines not covered by Morton (1991). All lines but three have wavelengths below 912 Å. Dots: Fuhr & Wiese (1991), Fuhr et al. (1988), Martin et al. (1988). Triangles: Wiese et al. (1966, 1969). Cross: Be I 1491.765 Å line (bad OP $f$-value).

**Fig. 3a-d.** Relative strengths of the ground level metal absorption lines from 228 to 8000 Å against log wavelength: **a** 228–550 Å, **b** 550–1349 Å, **c** 1349–3311 Å, **d** 3311–8000 Å. The strength of the strongest metal line, O V 629.730 Å, is set to 1.0. Hydrogen and helium lines are not shown, ionization is neglected (we assume that all atoms of an element are in the ion which produces the line that we show), and we assume solar abundances. The depths of all lines are equal to $10^{P-11.44}$, where $P$ is the expected width (strength) parameter from Eq. (2). Note that the C I line at 841Å does not have an experimental wavelength.

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