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Radiative transition probabilities in the O-like sequence⋆

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Abstract. In the present work a complete set of radiative transition rates is calculated for all for the O-like ions with $Z = 11-30$. Energy levels, oscillator strengths and A values are computed for all transitions within the $n = 2$ complex and are compared with previous calculations, where available. Calculations are carried out using the Superstructure code. The present work provides for the first time a self-consistent, complete set of A values necessary for the calculation of line emissivities and synthetic spectra for all the ions considered, filling several gaps in the existing literature. The present data are especially suited for the analysis of spectral lines emitted by the less-abundant elements in the universe, for which few if any data were available in the literature.

Key words. atomic data – atomic processes – radiation mechanisms: general – line: formation – Sun: corona

1. Introduction

Spectral lines emitted by ions belonging to the oxygen-like sequence have long been known in the literature for their diagnostic potential for astrophysical plasmas in a variety of different physical conditions. The importance of these ions is given by the rather prominent spectral lines that they generate from both allowed and forbidden transitions. Such lines have been long observed in all wavelength ranges. Allowed transitions within the $n = 2$ complex give rise to prominent lines in the extreme-ultraviolet spectrum, that have been used over the years for plasma diagnostics in solar and stellar plasmas in all conditions; forbidden transitions within the ground configuration levels give rise to a number of lines in the ultraviolet, visible and infrared ranges which have been observed in solar, stellar and in planetary nebulae spectra. Recently, allowed transitions from excited $n = 3$ configurations from several O-like ions have been observed in solar ultraviolet spectra (Kink et al. 1997; Kink & Engström 1997) and have been found to provide excellent temperature diagnostic tools when used in combination with forbidden lines within the ground configuration, usually found in their proximity. Moreover, lines from O-like ions from less abundant elements, such as P, Cl, K, Ti, Cr, Mn and Co, have been identified in solar spectra (Feldman et al. 2000; Feldman et al. 2004); these ions allow more accurate studies of the chemical composition of the observed plasmas.

The O-like isoelectronic sequence has been paid little attention in the past as far as electron excitation is concerned, but several authors studied O-like systems in an effort to determine the energies of their levels, their radiative rates and lifetimes. A few complete calculations of radiative data that encompass the whole isoelectronic sequence, with the exceptions of the very low stages of ionization, have been carried out by Cheng et al. (1979), Fawcett (1986) and Zhang & Sampson (2002). However, the latter two calculations only provided data for allowed transitions between the ground and the excited configurations, and do not allow to calculate level populations and line intensities. Cheng et al. (1979) included the three configurations in the $n = 2$ complex in their atomic model, and published a complete dataset of radiative data. Another complete dataset was provided by Froese Fischer & Tachiev (2004) and Tachiev & Froese Fischer (2002), but limited to the O-like ions with $Z \leq 20$. Galavis et al. (1997) provided radiative transition probabilities for forbidden transitions within the ground configuration of the O-like sequence up to Ni. A similar calculation was carried out by Froese Fischer & Saha (1983), Baluja & Zeippen (1988) and Vilkas et al. (1994): the latter two datasets however considered only the most abundant elements up to Ni. Calculations limited to a few ions between $Z = 26$ and $Z = 36$ have been reported by Feldman et al. (1985); Bhatia et al. (1979) published data for Si VII, S IX and Ar XI only, while Bhatia et al. (1980) and Bhatia (1982) considered only O-like Ti and Mn, respectively. These calculations were carried out mostly using a limited number of configurations in the atomic model. Recently, Bhatia et al. (2003a,b) and Bhatia & Landi (2003a,b) published complete data for a few individual ions (Ne III, Si VII, S IX and Ni XXI), while Lolergue et al. (1985) and Butler & Zeippen (2001) provided a complete dataset for Fe XIX. In general, all the less abundant ions in the

⋆ Tables 3–8 are also available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/434/365

O-like sequence with $20 \leq Z \leq 30$ have incomplete datasets, or their data have been calculated using limited atomic models. However, databases such as CHIANTI (Dere et al. 1997; Young et al. 2003), require dataset as complete, accurate and self-consistent as possible, in order to provide the astrophysical community with tools and data to carry out accurate plasma diagnostics. Of particular importance for these databases are complete sets of accurate A values and oscillator strengths.

The aim of the present work is to calculate a complete set of radiative transition probabilites (A values and oscillator strengths) for all possible $n = 2$ transitions in the O-like sequence for all ions with $11 \leq Z \leq 30$, in an effort to provide a complete, self-consistent and accurate dataset; we are mainly interested in providing a complete set of data for the less abundant elements in the O-like sequence (P,Cl, K, Ti, Cr, Mn, Co), for the first time. This will be done by using a comprehensive atomic model that includes all the relevant configurations in the O-like sequence, which is described in Sect. 2. The present results are compared with previous calculations, in order to assess their accuracy, in Sect. 3. Section 4 summarizes the results.

2. Atomic data

The atomic data have been calculated using computer programs originally developed at University College London. These programs have been updated over the years. The energy levels, oscillator strengths, and radiative transition rates have been calculated by using the Superstructure program described by Eissner et al. (1974). The configurations we are interested in are $2s^2 2p^4$, $2s2p^5$ and $2p^6$, giving rise to 10 fine-structure levels. In order to calculate accurate atomic level energies and radiative transition rates an atomic model including 24 configurations has been used. The configurations are listed below.

$2s^2 2p^4$
$2s2p^5$
$2p^6$

$2s^2 2p^3 3l$ $\quad l = \mathrm{s, p, d}$
$2s2p^4 3l$ $\quad l = \mathrm{s, p, d}$
$2p^5 3l$ $\quad l = \mathrm{s, p, d}$

$2s^2 2p^3 4l$ $\quad l = \mathrm{s, p, d, f}$
$2s2p^4 4l$ $\quad l = \mathrm{s, p, d, f}$
$2p^5 4l$ $\quad l = \mathrm{s, p, d, f.}$

The wavefunctions are of configuration interaction type and each configuration is expanded in terms of Slater orbitals. The radial functions are calculated in a scaled Thomas-Fermi-Amaldi potential. The potential depends upon parameters λ_{nl} which are determined variationally by optimizing the weighted sum of the term energies. The relativistic corrections are included by using the Breit-Pauli Hamiltonian as a perturbation to the nonrelativistic Hamiltonian. The Breit-Pauli Hamiltonian adopted in Superstructure includes mass variation, Darwin and spin-orbit operators, as well as spin-other orbit, mutual spin-orbit and spin-spin operators; more details can be found in Eissner et al. (1974). Energy levels, oscillator strengths, and radiative transition rates are calculated in intermediate coupling. The calculated energies are listed in Table 1 along with experimentally determined energies from the Edlen (1983); experimental energies for Fe XIX and Ni XXI come from Shirai et al. (2000). We use the calculated energies and the wave functions to calculate all the radiative data; oscillator strengths and A values are then corrected in order to take into account laboratory wavelengths. The resulting corrected A values and weighted oscillator strengths (obtained multiplying the corrected absorption oscillator strength for the statistical weight of the lower level of each transition) are given in Tables 3 to 8.

3. Comparison with earlier work

In the past, several different calculations have been carried out on O-like ions, some involving one or only a few ions, some providing datasets across the whole O-like sequence. In order to assess the accuracy of the present calculations, we have compared them with results found in the literature. The availability of many independent calculations carried out using different theoretical methods and approximations helps in assessing the accuracy of our results. Some of these calculations were carried out in the 1980s, when computers had a more limited computational capabilities, so atomic models had to be restricted to only a handful of configurations, at the expense of accuracy in the computed wavefunctions. With modern computers the situation is greatly improved and the set of configurations that now can be included is much larger. This allows to take into account with greater accuracy the interactions between different configurations and improve the results. Therefore, in our comparison, we will focus mostly on recent, sophisticated calculations, where available; we will also consider the comprehensive computations by Chang et al. (1979) and Froese Fischer & Saha (1983), given the accuracy of the approximations adopted in these works.

Table 2 compares energy levels obtained in the present calculations (ab initio results from the 24-configuration model) with the observed ones, and with those obtained by other calculations: Cheng et al. (1979), Tachiev & Froese Fischer (2002), Vilkas et al. (1994) and Zhang & Sampson (2002): all these works were carried out using different methods and approximations than Superstructure. The comparison is shown for Si VII, Ca XIII and Fe XIX. Results show that for Fe XIX all calculations have comparable accuracy and reproduce the observed energies within 1%; all calculations provide similar results. At low-Z, the comparison for Si VII shows that results from the more elaborate models from Tachiev & Froese Fischer (2002) and Vilkas et al. (1994) provide closer agreement with observations than those from Cheng et al. (1979) and the present work. The latter two calculations provide similar results for the excited configurations, while Cheng et al. (1979) has closer agreement with observations for the ground configuration than the present calculation. Results for Ca XIII show that the present calculation is better at reproducing observations than for Si VII, and differences from theother calculations are smaller than at lower Z. However, Tachiev & Froese Fischer (2002) and Vilkas et al. (1994) still have better agreement with observed energies. This seems to indicate that the approximations in Superstructure are

Table 1. Energies for the $n = 2$ levels in the O-like isoelectronic sequence. The first entry for each level is the experimental value, the second entry is the theoretical value calculated in the present work. Experimental energies come from Edlen (1983), with the only exception of Fe XIX and Ni XXI, which are taken from Shirai et al. (2000). Energies are in cm^{-1}.

	Level	Na IV	Mg V	Al VI	Si VII	P VIII	S IX	Cl X
1	$2s^2 2p^4\ ^3P_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	$2s^2 2p^4\ ^3P_1$	1107.00	1783.00	2733.00	4030.00	5748.00	7985.00	10 847.00
		1193.45	1902.59	2885.96	4227.13	5994.73	8286.25	11 200.38
3	$2s^2 2p^4\ ^3P_0$	1576.00	2521.00	3827.00	5565.00	7817.00	10 648.00	14 127.00
		1700.78	2689.77	4039.66	5837.06	8142.86	11 032.93	14 562.90
4	$2s^2 2p^4\ ^1D_2$	30 841.00	35 925.00	41 147.00	46 569.80	52 256.00	58 295.00	64 872.00
		34 113.41	39 207.65	44 450.77	49 906.43	55 638.42	61 731.11	68 281.37
5	$2s^2 2p^4\ ^1S_0$	66 496.00	77 287.00	88 206.00	99 341.00	110 799.00	122 700.00	135 206.00
		66 821.75	77 893.24	89 070.41	100 441.09	112 105.98	124 198.97	136 879.97
6	$2s2p^5\ ^3P_2$	243 682.00	283 212.00	323 005.00	363 170.00	403 784.00	444 987.00	486 894.00
		254 177.42	293 686.30	333 475.62	373 637.22	414 262.95	455 459.64	497 350.13
7	$2s2p^5\ ^3P_1$	244 688.00	284 831.00	325 476.00	366 786.00	408 890.00	451 995.00	496 276.00
		255 249.70	295 394.85	336 062.39	377 406.31	419 562.82	462 704.18	507 005.01
8	$2s2p^5\ ^3P_0$	245 238.00	285 715.00	326 824.00	368 761.00	411 701.00	455 890.00	501 554.00
		255 831.17	296 319.07	337 466.15	379 458.53	422 469.42	466 716.91	512 425.76
9	$2s2p^5\ ^1P_1$	343 688.00	397 485.00	451 383.00	505 650.00	560 476.00	616 073.00	672 630.00
		365 154.97	418 584.83	472 175.99	526 207.81	580 852.94	636 283.80	692 684.19
10	$2p^6\ ^1S_0$	570 823.00	662 973.00	755 634.00	849 057.00	943 504.00	1 039 219.00	1 136 464.00
		608 554.59	700 200.52	792 386.02	885 458.94	979 613.13	1 075 064.39	1 172 051.92

	Level	Ar XI	K XII	Ca XIII	Sc XIV	Ti XV	V XVI
1	$2s^2 2p^4\ ^3P_2$	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00
2	$2s^2 2p^4\ ^3P_1$	14 455.00	18 945.00	24 465.00	31 183.00	39 277.00	48 939.00
		14 878.30	19 431.73	25 015.93	31 792.36	39 935.96	49 633.30
3	$2s^2 2p^4\ ^3P_0$	18 307.00	23 224.00	28 880.00	35 259.00	42 309.00	49 944.00
		18 809.53	23 779.34	29 487.67	35 909.94	42 988.33	50 632.70
4	$2s^2 2p^4\ ^1D_2$	71 834.00	79 589.00	88 202.00	97 846.00	108 717.00	121 025.00
		75 409.39	83 245.44	91 945.01	101 679.87	112 639.06	125 025.78
5	$2s^2 2p^4\ ^1S_0$	148 513.00	162 868.00	178 568.00	195 975.00	215 509.00	237 651.00
		150 351.09	164 853.79	180 686.70	198 203.88	217 819.70	240 002.03
6	$2s2p^5\ ^3P_2$	529 643.00	573 384.00	618 280.00	664 511.00	712 268.00	761 757.00
		540 055.11	583 729.82	628 533.10	674 636.11	722 226.55	771 499.88
7	$2s2p^5\ ^3P_1$	541 936.00	589 190.00	638 266.00	689 399.00	742 838.00	798 835.00
		552 681.02	599 918.72	648 948.96	700 000.35	753 312.56	809 124.41
8	$2s2p^5\ ^3P_0$	548 958.00	598 387.00	650 149.00	704 574.00	762 020.00	822 869.00
		559 875.12	609 316.21	661 061.21	715 431.43	772 774.58	833 454.94
9	$2s2p^5\ ^1P_1$	730 362.00	789 501.00	850 299.00	913 031.00	978 007.00	1 045 564.00
		750 254.32	809 209.00	869 795.54	932 280.09	996 961.58	1 064 162.03
10	$2p^6\ ^1S_0$	1 235 523.00	1 336 699.00	1 440 313.00	1 546 706.00	1 656 253.00	1 769 343.00
		1 270 831.51	1 371 684.84	1 474 924.94	1 580 878.35	1 689 902.54	1 802 367.88

	Level	Cr XVII	Mn XVIII	Fe XIX	Co XX	Ni XXI	Cu XXII	Zn XXIII
1	$2s^2 2p^4\ ^3P_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	$2s^2 2p^4\ ^3P_0$	58 050.00	66 505.00	75 250.00	83 992.00	92 821.00	101 662.00	110 437.00
		58 727.50	67 147.89	75 762.78	84 467.57	93 161.43	101 787.58	110 302.99
3	$2s^2 2p^4\ ^3P_1$	60 375.00	73 800.00	89 441.00	107 527.00	128 290.00	152 036.00	178 973.00
		61 081.42	74 490.02	90 075.45	108 060.68	128 672.04	152 158.78	178 763.14
4	$2s^2 2p^4\ ^1D_2$	134 991.00	150 851.00	168 852.00	189 233.00	212 250.00	238 204.00	267 325.00
		139 055.13	154 955.05	172 966.13	193 306.74	216 237.23	242 011.68	270 881.37
5	$2s^2 2p^4\ ^1S_0$	262 926.00	291 899.00	325 140.00	363 262.00	406 800.00	456 394.00	512 557.00
		265 260.76	294 157.15	327 247.36	365 084.46	408 225.26	457 231.74	512 625.64
6	$2s2p^5\ ^3P_2$	813 196.00	866 813.00	922 890.00	981 541.00	1 043 150.00	1 107 959.00	1 176 226.00
		822 657.32	875 940.80	931 566.46	989 740.54	1 050 729.92	1 114 800.24	1 182 161.96
7	$2s2p^5\ ^3P_1$	857 644.00	919 516.00	984 740.00	1 053 409.00	1 125 850.00	1 202 337.00	1 282 957.00
		867 669.70	929 210.18	993 951.18	1 062 125.65	1 133 919.29	1 209 560.13	1 289 181.47
8	$2s2p^5\ ^3P_0$	887 524.00	956 409.00	1 030 020.00	1 108 665.00	1 192 960.00	1 283 451.00	1 380 576.00
		897 851.41	966 397.08	1 039 478.05	1 117 588.05	1 201 123.77	1 290 615.21	1 386 504.09
9	$2s2p^5\ ^1P_1$	1 116 069.00	1 189 924.00	1 267 600.00	1 349 489.00	1 436 400.00	1 528 248.00	1 626 251.00
		1 134 246.09	1 207 579.57	1 284 610.86	1 365 785.12	1 451 591.18	1 542 584.42	1 639 303.85
10	$2p^6\ ^1S_0$	1 886 387.00	2 007 816.00	2 134 180.00	2 265 677.00	2 403 500.00	2 546 794.00	2 697 367.00
		1 918 673.45	2 039 227.89	2 164 475.87	2 294 859.33	2 430 831.25	2 572 923.47	2 721 568.65

Table 2. Comparison of observed and computed energy levels in the O-like sequence. Only the cases of Si VII, Ca XIII and Fe XIX are reported. E_{obs}: observed energy level, from Edlen (1983 – Si VII, Ca XIII) and Shirai et al. (2000 – Fe XIX); 24C: present work, 24-configuration calculation; C79: Cheng et al. (1979); TFF02: Tachiev & Froese Fischer (2002); V94: Vilkas et al. (1994); ZS02: Zhang & Sampson (2002).

Si VII					
Level	E_{obs}	24C	C79	TFF02	V94
1	0	0	0	0	0
2	4030	4227	3997	4034	4017
3	5565	5837	5456	5546	5566
4	46 570	49 906	48 693	46 910	46 520
5	99 341	100 441	95 618	99 315	99 134
6	363 170	373 637	372 074	364 085	362 832
7	366 786	377 406	375 669	367 698	364 880
8	368 761	379 459	377 559	369 675	366 849
9	505 650	526 208	527 122	507 551	504 125
10	849 507	885 459	888 769	852 002	844 169
Ca XIII					
Level	E_{obs}	24C	C79	TFF02	V94
1	0	0	0	0	0
2	24 465	25 016	24 646	24 800	24 209
3	28 880	29 488	28 857	28 832	28 737
4	88 202	91 045	91 046	89 087	88 287
5	178 568	180 687	174 355	178 643	178 016
6	618 280	628 533	627 311	621 713	616 067
7	638 266	648 949	647 961	641 939	635 927
8	650 149	661 061	659 795	653 989	647 728
9	850 299	869 796	872 522	854 658	847 229
10	1 440 313	1 474 925	1 480 522	1 445 483	1 434 221
Fe XIX					
Level	E_{obs}	24C	C79	ZS02	V94
1	0	0	0	0	0
2	75 250	75 762	76 016	74 160	74 712
3	89 441	90 075	89 003	89 129	87 559
4	168 852	172 966	170 557	170 422	167 882
5	325 140	327 247	322 602	321 201	321 124
6	922 890	931 566	930 851	930 902	917 431
7	984 740	993 951	993 068	993 123	978 242
8	1 030 020	1 039 478	1 037 725	1 037 786	1 022 750
9	1 267 600	1 284 611	1 287 937	1 289 413	1 258 927
10	2 134 180	2 164 476	2 172 572	2 176 091	2 120 179

less accurate in calculating ab initio energy levels for lower stages of ionization than the other methods.

To check how this more limited accuracy is propagated to the radiative transition rates, which are the main focus of the present work, we have carried out extensive comparisons of A values in the present work with those from other authors, with special emphasys on the lower stages of ionization.

The forbidden transitions within the ground configurations are very important both for level population calculation and because they provide some strong lines observed in astrophysical spectra. We have compared our results with those obtained by Galavis et al. (1997 – G97), Baluja & Zeippen (1988 – BZ88), Tachiev & Froese Fischer (2002 – TFF02), Froese Fischer & Saha (1983 – FS83), and Cheng et al. (1979 – C79). Agreement within 10% is found for all transitions in all ions except for the results from Cheng et al. (1979), who show differences from all other calculations by 10% to 30%. Transitions involving $\Delta J = 2$ and the ^{3}P ground term ($^3P_0$–$^1D_2$ and $^3P_2$–$^1S_0$) show a larger discrepancy. An example is given in Table 9, where a detailed comparison is shown for Si VII. The A value of the $^3P_0$–$^1D_2$ transition is higher in the present calculation by 20%: this disagreement decreases with Z, and the different calculations agree within 10% for all ions heavier than K XII. Problems with the $^3P_2$–$^1S_0$ transition are persistent in all ions and cause the various calculations to disagree up to 30%. However, both transitions (electric quadrupole) have very limited influence on the level populations and do not give rise to any observed lines. An example of the disagreement is shown in Table 9, where a comparison between the results from the present work (24C) and other sources are presented for Si VII. For comparison purposes, we have also included the results (6C) obtained with the same codes and approximations of the present calculations, but adopting a more limited atomic model, that includes the six lowest configurations only: this model, more limited than all

Table 3. *A* values for the O-like sequence (Na IV to S IX). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Na IV	Mg V	Al VI	Si VII	P VIII	S IX
1 -	2	M1	3.048-02	1.273-01	4.575-01	1.467+00	4.249+00	1.136+01
1 -	3	E2	1.820-07	1.062-06	5.199-06	2.172-05	8.034-05	2.648-04
1 -	4	M1	5.925-01	1.798+00	4.863+00	1.186+01	2.688+01	5.720+01
1 -	5	E2	8.670-03	2.049-02	4.419-02	8.592-02	1.571-01	2.703-01
1 -	6	E1	6.077+09	7.364+09	8.740+09	1.019+10	1.172+10	1.332+10
1 -	7	E1	3.424+09	4.172+09	4.985+09	5.866+09	6.815+09	7.845+09
1 -	8	M2	2.314+00	3.792+00	5.753+00	8.267+00	1.134+01	1.508+01
1 -	9	E1f	1.479+07	3.285+07	6.812+07	1.308+08	2.364+08	4.043+08
1 -	10	E2	1.502+02	3.172+02	6.284+02	1.136+03	1.951+03	3.195+03
2 -	3	M1	5.562-03	2.166-02	7.108-02	1.945-01	4.753-01	1.010+00
2 -	4	M1	1.769-01	5.146-01	1.321+00	3.021+00	6.345+00	1.234+01
2 -	5	M1	8.261+00	2.417+01	6.336+01	1.509+02	3.339+02	6.940+02
2 -	6	E1	1.997+09	2.408+09	2.840+09	3.290+09	3.752+09	4.225+09
2 -	7	E1	2.024+09	2.451+09	2.909+09	3.394+09	3.902+09	4.436+09
2 -	8	E1	8.154+09	9.911+09	1.180+10	1.381+10	1.597+10	1.825+10
2 -	9	E1f	3.223+05	7.129+05	1.529+06	3.104+06	5.923+06	1.077+07
2 -	10	M1	2.465+00	6.233+00	1.580+01	3.647+01	7.856+01	1.590+02
3 -	4	E2	3.661-05	7.762-05	1.534-04	2.806-04	4.875-04	8.079-04
3 -	6	M2	4.998-01	8.425-01	1.325+00	1.982+00	2.870+00	4.042+00
3 -	7	E1	2.680+09	3.240+09	3.834+09	4.457+09	5.105+09	5.778+09
3 -	9	E1f	4.582+05	1.382+06	3.200+06	6.618+06	1.273+07	2.318+07
4 -	5	E2	3.600+00	4.329+00	5.080+00	5.876+00	6.712+00	7.610+00
4 -	6	E1f	1.944+06	4.558+06	9.773+06	1.923+07	3.553+07	6.198+07
4 -	7	E1f	1.642+05	3.496+05	6.840+05	1.225+06	2.037+06	3.148+06
4 -	8	M2	2.274+00	3.897+00	6.228+00	9.490+00	1.394+01	1.994+01
4 -	9	E1	2.934+10	3.507+10	4.103+10	4.720+10	5.353+10	6.005+10
4 -	10	E2	1.781+05	2.481+05	2.753+05	2.993+05	3.219+05	3.438+05
5 -	6	M2	3.092-01	4.939-01	7.384-01	1.049+00	1.426+00	1.870+00
5 -	7	E1f	3.819+05	8.450+05	1.776+06	3.504+06	6.619+06	1.199+07
5 -	9	E1	1.423+09	1.980+09	2.498+09	3.010+09	3.531+09	4.062+09
6 -	7	M1	2.288-02	9.538-02	3.374-01	1.062+00	2.990+00	7.729+00
6 -	8	E2	1.666-07	9.856-07	4.864-06	2.114-05	8.105-05	2.808-04
6 -	9	M1	1.072+00	3.250+00	8.711+00	2.124+01	4.793+01	1.016+02
6 -	10	M2	4.894+01	7.999+01	1.227+02	1.789+02	2.513+02	3.429+02
7 -	8	M1	8.971-03	3.726-02	1.315-01	4.154-01	1.198+00	3.184+00
7 -	9	M1	6.403-01	1.906+00	5.004+00	1.194+01	2.628+01	5.418+01
7 -	10	E1f	2.800+06	7.519+06	1.677+07	3.473+07	6.751+07	1.243+08
8 -	9	M1	8.136-01	2.424+00	6.347+00	1.504+01	3.277+01	6.666+01
9 -	10	E1	2.065+10	2.603+10	3.200+10	3.829+10	4.490+10	5.181+10

the others, simulates the models adopted in many early calculations. The differences rise to 20% in all transitions, except those with $\Delta J = 2$, where differences range from 30% to a factor of 2.

Table 10 shows the comparison between several different calculations of allowed (E1) and spin-forbidden E1 transitions between the ground and the $2s2p^5$ configurations, and the $2s2p^5$ and the $2p^6$ configurations for S IX. Table 10 also reports the data published by Bhatia & Landi (2003b), calculated using a 6-configuration atomic model (6C): these *A* values are usually higher than those from the present calculation by 10% to 40%, a clear indication that a limited number of

Table 4. Weighted oscillator strengths for the O-like sequence (Na IV to S IX). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Na IV	Mg V	Al VI	Si VII	P VIII	S IX
1 -	2	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	3	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	6	E1	7.675-01	6.886-01	6.283-01	5.796-01	5.393-01	5.044-01
1 -	7	E1	2.574-01	2.314-01	2.118-01	1.962-01	1.834-01	1.728-01
1 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	9	E1f	5.635-04	9.355-04	1.504-03	2.302-03	3.386-03	4.793-03
1 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	3	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	5	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	6	E1	2.545-01	2.280-01	2.077-01	1.913-01	1.776-01	1.659-01
2 -	7	E1	1.535-01	1.377-01	1.257-01	1.161-01	1.080-01	1.012-01
2 -	8	E1	2.052-01	1.844-01	1.685-01	1.557-01	1.453-01	1.365-01
2 -	9	E1f	1.236-05	2.049-05	3.419-05	5.550-05	8.662-05	1.310-04
2 -	10	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	4	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	7	E1	2.040-01	1.829-01	1.668-01	1.537-01	1.428-01	1.335-01
3 -	9	E1f	1.762-05	3.985-05	7.189-05	1.191-04	1.876-04	2.845-04
4 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	6	E1f	3.219-04	5.590-04	9.228-04	1.439-03	2.157-03	3.109-03
4 -	7	E1f	1.616-05	2.539-05	3.808-05	5.374-05	7.205-05	9.140-05
4 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	9	E1	1.349+00	1.207+00	1.097+00	1.008+00	9.326-01	8.685-01
4 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	7	E1f	5.413-05	8.827-05	1.420-04	2.205-04	3.352-04	4.974-04
5 -	9	E1	8.334-02	8.690-02	8.522-02	8.206-02	7.857-02	7.509-02
6 -	7	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	8	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	10	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	8	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	10	E1f	3.949-05	7.887-05	1.359-04	2.240-04	3.543-04	5.409-04
8 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
9 -	10	E1	6.004-01	5.540-01	5.186-01	4.870-01	4.590-01	4.340-01

configurations in the atomic model decreases the accuracy of the radiative rates. Excellent agreement, within 10%, is found between the present calculation and the results from Tachiev & Froese Fischer (2002); the older calculations by Fawcett (1986) are higher than the latter two datasets by 10−15%. Zhang & Sampson (2002) *A* values are always

Table 5. *A* values for the O-like sequence (Cl X to V XVI). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Cl X	Ar XI	K XII	Ca XIII	Sc XIV	Ti XV	V XVI
1 -	2	M1	2.838+01	6.688+01	1.497+02	3.198+02	6.568e+02	1.300+03	2.486e+03
1 -	3	E2	7.912-04	2.140-03	5.437-03	1.269-02	2.746e-02	5.557-02	1.053e-01
1 -	4	M1	1.162+02	2.234+02	4.162+02	7.518+02	1.322e+03	2.271+03	3.825e+03
1 -	5	E2	4.443-01	6.869-01	1.032+00	1.493+00	2.085e+00	2.831+00	3.744e+00
1 -	6	E1	1.499+10	1.674+10	1.858+10	2.050+10	2.253e+10	2.468+10	2.696e+10
1 -	7	E1	8.967+09	1.020+10	1.158+10	1.311+10	1.484e+10	1.683+10	1.911e+10
1 -	8	M2	1.944+01	2.452+01	3.029+01	3.685+01	4.406e+01	5.212+01	6.104e+01
1 -	9	E1f	6.602+08	1.029+09	1.543+09	2.232+09	3.121e+09	4.229+09	5.566e+09
1 -	10	E2	5.030+03	8.749+03	1.113+04	1.583+04	2.189e+04	2.953+04	3.894e+04
2 -	3	M1	1.879+00	2.942+00	4.103+00	4.489+00	3.443e+00	1.386+00	4.913e-02
2 -	4	M1	2.261+01	3.852+01	6.267+01	9.730+01	1.445e+02	2.067+02	2.855e+02
2 -	5	M1	1.370+03	2.575+03	4.675+03	8.197+03	1.393e+04	2.306+04	3.728e+04
2 -	6	E1	4.708+09	5.197+09	5.697+09	6.202+09	6.715e+09	7.234+09	7.760e+09
2 -	7	E1	4.995+09	5.581+09	6.194+09	6.837+09	7.512e+09	8.217+09	8.954e+09
2 -	8	E1	2.070+10	2.332+10	2.613+10	2.917+10	3.247e+10	3.607+10	4.002e+10
2 -	9	E1f	1.869+07	3.151+07	5.134+07	8.138+07	1.259e+08	1.908+08	2.836e+08
2 -	10	M1	3.061+02	6.092+02	9.874+02	1.681+03	2.776e+03	4.460+03	6.990e+03
3 -	4	E2	1.300-03	1.990-03	2.996-03	4.473-03	6.683e-03	1.011-02	1.567e-02
3 -	6	M2	5.601+00	7.640+00	1.030+01	1.377+01	1.827e+01	2.408+01	3.155e+01
3 -	7	E1	6.476+09	7.202+09	7.950+09	8.729+09	9.547e+09	1.040+10	1.131e+10
3 -	9	E1f	4.039+07	6.772+07	1.097+08	1.721+08	2.613e+08	3.844+08	5.470e+08
4 -	5	E2	8.548+00	9.694+00	1.110+01	1.281+01	1.496e+01	1.790+01	2.198e+01
4 -	6	E1f	1.030+08	1.630+08	2.481+08	3.639+08	5.159e+08	7.088+08	9.460e+08
4 -	7	E1f	4.529+06	5.998+06	7.279+06	7.916+06	7.419e+06	5.488+06	2.476e+06
4 -	8	M2	2.788+01	3.846+01	5.226+01	7.023+01	9.358e+01	1.236+02	1.622e+02
4 -	9	E1	6.671+10	7.359+10	8.065+10	8.787+10	9.529e+10	1.029+11	1.108e+11
4 -	10	E2	3.653+05	4.426+05	4.083+05	4.299+05	4.517e+05	4.737+05	4.962e+05
5 -	6	M2	2.374+00	2.928+00	3.503+00	4.073+00	4.604e+00	5.047+00	5.363e+00
5 -	7	E1f	2.097+07	3.521+07	5.729+07	9.019+07	1.374e+08	2.019+08	2.858e+08
5 -	9	E1	4.606+09	5.165+09	5.735+09	6.314+09	6.901e+09	7.488+09	8.072e+09
6 -	7	M1	1.854+01	4.204+01	8.847+01	1.782+02	3.442e+02	6.361+02	1.131e+03
6 -	8	E2	8.904-04	2.647-03	7.195-03	1.857-02	4.588e-02	1.077-01	2.422e-01
6 -	9	M1	2.045+02	3.947+02	7.340+02	1.322+03	2.318e+03	3.970+03	6.662e+03
6 -	10	M2	4.574+02	7.124+02	7.731+02	9.862+02	1.246e+03	1.561+03	1.945e+03
7 -	8	M1	7.921+00	1.870+01	4.183+01	8.973+01	1.873e+02	3.771+02	7.392e+02
7 -	9	M1	1.056+02	1.965+02	3.512+02	6.053+02	1.010e+03	1.641+03	2.600e+03
7 -	10	E1f	2.190+08	4.119+08	6.085+08	9.706+08	1.509e+09	2.296+09	3.424e+09
8 -	9	M1	1.277+02	2.327+02	4.058+02	6.790+02	1.094e+03	1.704+03	2.574e+03
9 -	10	E1	5.905+10	7.291+10	7.454+10	8.284+10	9.152e+10	1.006+11	1.100e+11

overestimated by 15% to 40%, the differences being largest for the forbidden transitions. Similar overestimations are found for the Cheng et al. (1979) data.

In general, agreement between the present calculation and results from the most sophisticated calculations available in the literature is within 10%.

Table 6. Weighted oscillator strengths for the O-like sequence (Cl X to V XVI). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Cl X	Ar XI	K XII	Ca XIII	Sc XIV	Ti XV	V XVI
1 -	2	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	3	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	6	E1	4.743-01	4.476-01	4.238-01	4.022-01	3.827-01	3.649-01	3.485-01
1 -	7	E1	1.638-01	1.563-01	1.501-01	1.448-01	1.406-01	1.372-01	1.348-01
1 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	9	E1f	6.566-03	8.677-03	1.114-02	1.389-02	1.685-02	1.990-02	2.291-02
1 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	3	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	5	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	6	E1	1.558-01	1.469-01	1.390-01	1.319-01	1.256-01	1.198-01	1.145-01
2 -	7	E1	9.538-02	9.025-02	8.572-02	8.167-02	7.802-02	7.470-02	7.165-02
2 -	8	E1	1.289-01	1.224-01	1.167-01	1.118-01	1.074-01	1.036-01	1.002-01
2 -	9	E1f	1.920-04	2.767-04	3.891-04	5.370-04	7.288-04	9.745-04	1.285-03
2 -	10	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	4	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	7	E1	1.254-01	1.182-01	1.117-01	1.058-01	1.004-01	9.534-02	9.074-02
3 -	9	E1f	4.192-04	6.010-04	8.405-04	1.147-03	1.526-03	1.976-03	2.483-03
4 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	6	E1f	4.335-03	5.832-03	7.631-03	9.714-03	1.205-02	1.459-02	1.728-02
4 -	7	E1f	1.095-04	1.221-04	1.261-04	1.177-04	9.541-05	6.142-05	2.426-05
4 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	9	E1	8.127-01	7.637-01	7.201-01	6.808-01	6.453-01	6.126-01	5.831-01
4 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	7	E1f	7.239-04	1.023-03	1.419-03	1.921-03	2.539-03	3.267-03	4.084-03
5 -	9	E1	7.176-02	6.865-02	6.572-02	6.298-02	6.040-02	5.795-02	5.565-02
6 -	7	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	8	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	10	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	8	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	10	E1f	8.015-04	1.198-03	1.634-03	2.263-03	3.080-03	4.127-03	5.452-03
8 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
9 -	10	E1	4.117-01	4.036-01	3.734-01	3.569-01	3.419-01	3.281-01	3.149-01

Data calculated for Ca XIII in the present work are in excellent agreement (within 10%) with results from Tachiev & Froese Fischer (2002) and Vilkas et al. (1994); Fawcett (1986) is slightly higher than the present calculation while Zhang & Sampson (2002) overestimate A values by up to a factor of 2 in the worst cases. Cheng et al. (1979) results are also higher and

Table 7. *A* values for the O-like sequence (Cr XVII to Zn XXIII). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Cr XVII	Mn XVIII	Fe XIX	Co XX	Ni XXI	Cu XXII	Zn XXIII
1 -	2	E2	1.872-01	3.134-01	4.976-01	7.399-01	1.066+00	1.469+00	1.943+00
1 -	3	M1	4.609+03	8.306+03	1.458+04	2.488+04	4.177+04	6.850+04	1.103+05
1 -	4	M1	6.327+03	1.030+04	1.652+04	2.617+04	4.083+04	6.302+04	9.588+04
1 -	5	E2	4.833+00	6.110+00	7.581+00	9.261+00	1.116+01	1.332+01	1.565+01
1 -	6	E1	2.941+10	3.205+10	3.492+10	3.805+10	4.149+10	4.532+10	4.955+10
1 -	7	E1	2.177+10	2.488+10	2.855+10	3.287+10	3.801+10	4.408+10	5.125+10
1 -	8	M2	7.092+01	8.189+01	9.418+01	1.079+02	1.241+02	1.415+02	1.622+02
1 -	9	E1f	7.126+09	8.890+09	1.083+10	1.289+10	1.503+10	1.717+10	1.927+10
1 -	10	E2	5.029+04	6.374+04	7.949+04	9.766+04	1.185+05	1.421+05	1.689+05
2 -	3	M1	1.962-01	5.835+00	4.117+01	1.793+02	5.852+02	1.597+03	3.863+03
2 -	4	E2	2.514-02	4.196-02	7.269-02	1.324-01	2.435-01	4.596-01	8.726-01
2 -	6	M2	4.107+01	5.314+01	6.836+01	8.755+01	1.110+02	1.416+02	1.793+02
2 -	7	E1	1.228+10	1.334+10	1.451+10	1.584+10	1.736+10	1.911+10	2.116+10
2 -	9	E1f	7.523+08	9.989+08	1.281+09	1.589+09	1.907+09	2.218+09	2.509+09
3 -	4	M1	3.823+02	4.976+02	6.320+02	7.899+02	9.573+02	1.147+03	1.339+03
3 -	5	M1	5.904+04	9.180+04	1.404+05	2.119+05	3.151+05	4.640+05	6.731+05
3 -	6	E1	8.293+09	8.834+09	9.383+09	9.940+09	1.050+10	1.107+10	1.165+10
3 -	7	E1	9.725+09	1.051+10	1.133+10	1.215+10	1.299+10	1.381+10	1.462+10
3 -	8	E1	4.434+10	4.913+10	5.445+10	6.033+10	6.692+10	7.428+10	8.253+10
3 -	9	E1f	4.143+08	5.956+08	8.436+08	1.178+09	1.623+09	2.204+09	2.954+09
3 -	10	M1	1.071+04	1.610+04	2.374+04	3.443+04	4.917+04	6.916+04	9.608+04
4 -	5	E2	2.780+01	3.629+01	4.889+01	6.776+01	9.684+01	1.413+02	2.086+02
4 -	6	E1f	1.229+09	1.559+09	1.935+09	2.352+09	2.808+09	3.300+09	3.824+09
4 -	7	E1f	9.950+04	2.387+06	1.685+07	5.564+07	1.367+08	2.838+08	5.269+08
4 -	8	M2	2.116+02	2.746+02	3.548+02	4.560+02	5.863+02	7.499+02	9.592+02
4 -	9	E1	1.190+11	1.274+11	1.363+11	1.457+11	1.559+11	1.664+11	1.779+11
4 -	10	E2	5.194+05	5.431+05	5.681+05	5.942+05	6.226+05	6.519+05	6.847+05
5 -	6	M2	5.520+00	5.506+00	5.328+00	5.003+00	4.592+00	4.074+00	3.555+00
5 -	7	E1f	3.889+08	5.079+08	6.364+08	7.642+08	8.820+08	9.787+08	1.049+09
5 -	9	E1	8.651+09	9.224+09	9.798+09	1.038+10	1.098+10	1.160+10	1.227+10
6 -	7	M1	1.939+03	3.213+03	5.154+03	7.965+03	1.206+04	1.767+04	2.521+04
6 -	8	E2	5.246-01	1.097+00	2.225+00	4.351+00	8.383+00	1.569+01	2.877+01
6 -	9	M1	1.098+04	1.781+04	2.850+04	4.502+04	7.036+04	1.085+05	1.657+05
6 -	10	M2	2.411+03	2.976+03	3.663+03	4.498+03	5.520+03	6.750+03	8.269+03
7 -	8	M1	1.414+03	2.645+03	4.853+03	8.723+03	1.546+04	2.692+04	4.612+04
7 -	9	M1	4.030+03	6.131+03	9.173+03	1.355+04	1.975+04	2.840+04	4.058+04
7 -	10	E1f	5.016+09	7.231+09	1.026+10	1.437+10	1.983+10	2.695+10	3.618+10
8 -	9	M1	3.773+03	5.379+03	7.462+03	1.012+04	1.335+04	1.714+04	2.154+04
9 -	10	E1	1.198+11	1.299+11	1.403+11	1.509+11	1.615+11	1.720+11	1.823+11

are closer to those from Zhang & Samspson (2002). Similar results are also found for Si VII: although Fawcett (1986), Cheng et al. (1979) and Zhang & Sampson (2002) are always higher than the present calculations, results from Tachiev & Froese Fischer (2002) and Vilkas et al. (1994) usually agree within 10% with the present results, although a very few transitions show differences up to 25%.

Fe XIX has been paid a greater consideration in the literature due to the strength and importance of its spectral lines. Table 11 reports the comparison between the present calculation and other five datasets. Butler & Zeippen (2001) data show excellent agreement (within 10%) with the present calculation for all transitions; those from Vilkas et al. (1994) also are in excellent agreement, except for a few, weak

Table 8. Weighted oscillator strengths for the O-like sequence (Cr XVII to Zn XXIII). E1: electric dipole transitions; E1f: spin-forbidden E1 transitions; E2: electric quadrupole transitions; M1: magnetic dipole transitions; M2: magnetic quadrupole transitions.

Down	Up	Type	Cr XVII	Mn XVIII	Fe XIX	Co XX	Ni XXI	Cu XXII	Zn XXIII
1 -	2	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	3	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	6	E1	3.336-01	3.199-01	3.075-01	2.962-01	2.860-01	2.769-01	2.687-01
1 -	7	E1	1.332-01	1.324-01	1.325-01	1.333-01	1.349-01	1.372-01	1.401-01
1 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
1 -	9	E1f	2.574-02	2.825-02	3.033-02	3.185-02	3.278-02	3.309-02	3.279-02
1 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	3	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	4	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
2 -	7	E1	8.646-02	8.250-02	7.894-02	7.586-02	7.319-02	7.097-02	6.925-02
2 -	9	E1f	3.024-03	3.562-03	4.055-03	4.464-03	4.754-03	4.904-03	4.914-03
3 -	4	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	5	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
3 -	6	E1	1.097-01	1.054-01	1.013-01	9.757-02	9.409-02	9.090-02	8.786-02
3 -	7	E1	6.885-02	6.613-02	6.361-02	6.112-02	5.873-02	5.633-02	5.399-02
3 -	8	E1	9.722-02	9.460-02	9.232-02	9.030-02	8.856-02	8.704-02	8.575-02
3 -	9	E1f	1.673-03	2.152-03	2.735-03	3.436-03	4.269-03	5.237-03	6.348-03
3 -	10	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	5	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	6	E1f	2.005-02	2.281-02	2.552-02	2.810-02	3.051-02	3.272-02	3.471-02
4 -	7	E1f	8.574-07	1.818-05	1.139-04	3.354-04	7.368-04	1.374-03	2.298-03
4 -	8	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
4 -	9	E1	5.563-01	5.312-01	5.082-01	4.872-01	4.681-01	4.499-01	4.334-01
4 -	10	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	6	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
5 -	7	E1f	4.948-03	5.803-03	6.582-03	7.222-03	7.677-03	7.915-03	7.941-03
5 -	9	E1	5.349-02	5.147-02	4.964-02	4.801-02	4.662-02	4.542-02	4.449-02
6 -	7	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	8	E2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
6 -	10	M2	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	8	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
7 -	10	E1f	7.110-03	9.158-03	1.165-02	1.466-02	1.822-02	2.236-02	2.712-02
8 -	9	M1	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00	0.000+00
9 -	10	E1	3.028-01	2.913-01	2.803-01	2.696-01	2.591-01	2.486-01	2.382-01

A values. Data from Lolergue et al. (1985) tend to be higher than those of the latter calculations, but only by a limited amount. Discrepancies are also limited between the latter calculations and those from Fawcett (1986), Cheng et al. (1979), and Zhang & Sampson (2002), although the latter seems provide slightly overestimated *A* values for intercombination transitions.

The only experimental measurements of transition rates in the O-like sequence we are aware of are those by Flaig & Schartner (1985), who measured the absorption oscillator strengths for the $2s^22p^4\ ^1D_2-2s2p^5\ ^1P_1$ (4−9) and the $2s^22p^4\ ^1S_0-2s2p^5\ ^1P_1$ (5−9) transitions in Si VII. We have compared *A* values derived from these measurements using observed wavelengths from Edlen (1983) with those in the present computation and in earlier works. Results are listed in Table 12. This comparison is even more important since it involves one of the ions for which the present energy levels were less accurate than those from earlier calculations. Results show that good agreement (within 10%) is found between the measured *A* value for the 4−9 transition and the results obtained in the present work, Tachiev & Froese Fischer (2002) and Vilkas et al. (1994), while Zhang & Sampson (2002) and

Table 9. Comparison between different calculations of O-like radiative data: forbidden transitions within the Si VII ground configuration. 24C: present calculation; 6C: 6-configuration calculation described in Bhatia & Landi (2003a); G97: Galavis et al. (1997); TFF02: Tachiev & Froese Fischer (2002); BZ88: Baluja & Zeippen (1988); FS83: Froese Fischer & Saha (1983) (corrected with the experimental wavelengths); C79: Cheng et al. (1979).

Transition	24C	6C	G97	TFF02	BZ88	FS83	C79
$^3P_2-^3P_1$	1.467+00	1.749+00	1.465+00	1.470+00	1.472+00	1.470+00	1.430+00
$^3P_2-^3P_0$	2.173-05	2.762-05	2.072-05	2.007-05	2.070-05	2.152-05	1.828-05
$^3P_1-^3P_0$	1.944-01	2.227-01	1.964-01	1.862-01	1.973-01	1.964-01	1.670-01
$^3P_2-^1D_2$	1.180+01	1.469+01	1.232+01	1.257+01	1.183+01	1.173+01	1.456+01
$^3P_1-^1D_2$	3.028+00	3.746+00	3.139+00	3.210+00	3.016+00	2.986+00	3.910+00
$^3P_0-^1D_2$	2.815-04	4.822-04	2.110-04		2.270-04	2.273-04	3.547-04
$^3P_2-^1S_0$	8.666-02	7.006-02	1.032-01	1.025-01	9.810-02	9.003-02	8.085-02
$^3P_1-^1S_0$	1.510+02	1.557+02	1.397+02	1.423+02	1.414+02	1.396+02	1.539+02
$^1D_2-^1S_0$	5.876+00	3.220+00	5.721+00		5.792+00	5.894+00	3.341+00

Table 10. Comparison between different calculations of O-like A values: spin-forbidden E1 and allowed transitions between the $2s^22p^4$ and $2s2p^5$ configurations, and between the $2s2p^5$ and $2p^6$ configurations (last two transitions) for S IX. 24C: Present calculation; 6C: 6-configuration calculation described in Bhatia & Landi (2003b); F86: Fawcett (1986); ZS02: Zhang & Sampson (2002); TFF02: Tachiev & Froese Fischer (2002); C79: Cheng et al. (1979).

Transition	24C	6C	F86	ZS02	TFF02	C79
$^3P_2-^3P_2$	1.332+10	1.494+10	1.420+10	1.571+10	1.248+10	1.642+10
$^3P_2-^3P_1$	7.845+09	8.796+09	8.348+09	9.284+09	7.361+09	9.685+09
$^3P_2-^1P_1$	4.043+08	4.911+08		4.723+08	4.092+08	5.648+08
$^3P_1-^3P_2$	4.225+09	4.744+09	4.537+09	4.988+09	3.955+09	5.219+09
$^3P_1-^3P_1$	4.436+09	4.979+09	4.735+09	5.244+09	4.157+09	5.477+09
$^3P_1-^3P_0$	1.825+10	2.048+10	1.952+10	2.163+10	1.712+10	2.254+10
$^3P_1-^1P_1$	1.077+07	1.235+07		1.171+07	1.052+07	4.434+07
$^3P_0-^3P_1$	5.778+09	6.485+09	6.194+09	6.839+09	5.417+09	7.127+09
$^3P_0-^1P_1$	2.318+07	2.681+07		3.193+07	2.209+07	3.507+07
$^1D_2-^3P_2$	6.198+07	7.161+07		7.058+07	5.973+07	8.287+07
$^1D_2-^3P_1$	3.148+06	3.375+06		5.391+06	3.156+06	6.343+06
$^1D_2-^1P_1$	6.005+10	7.133+10	6.340+10	7.017+10	5.736+10	7.521+10
$^1S_0-^3P_1$	1.199+07	1.711+07		1.559+07	1.048+07	1.847+07
$^1S_0-^1P_1$	4.062+09	4.549+09	4.761+09	4.863+09	3.967+09	5.385+09
$^3P_1-^1S_0$	1.243+08	1.695+08		1.430+08	1.249+08	1.760+08
$^1P_1-^1S_0$	5.181+10	7.240+10	5.467+10	6.553+10	4.868+10	7.274+10

Cheng et al. (1979) overestimate the A value; the agreement for the 5−9 transition is worse (25−35%) than for the 4−9 one, but again better agreement is found with results obtained in the present work, Tachiev & Froese Fischer (2002) and Vilkas et al. (1994).

4. Conclusions

In the present work we have calculated a complete, self-consistent dataset of atomic data and transition probabilities for all the most abundant ions in the O-like sequence with Z included between 11 and 30. The main aim of the present work is to develop complete sets of radiative data (A values and oscillator strengths) for the less-abundant elements (P, Cl, K, Ti, Cr, Mn, Co), unavailable in the literature. Results have been compared with earlier calculations, where available; energy levels have been found to be slightly less accurate than previous work for the lighter ions, and in very good agreement for the heavier ions. Despite this, the accuracy of the A values and oscillator strengths, the main topic of the present work, is comparable to, or better than, all the most sophysticated calculations available in the literature. A comparison with Si VII oscillator strengths measured in the laboratory confirms the accuracy of the radiative values of the present calculation.

This dataset is the first one to provide complete radiative data for all the elements considered, and fills a few gaps for the

Table 11. Comparison between different calculations of O-like A values: spin-forbidden E1 and allowed transitions between the $2s^22p^4$ and $2s2p^5$ configurations, and between the $2s2p^5$ and $2p^6$ configurations (last two transitions) for Fe XIX. 24C: Present calculation; BZ01: Butler & Zeippen (2001); L85: Lolergue et al. (1985); ZS02: Zhang & Sampson (2002); F86: Fawcett (1986); V94: Vilkas et al. (1994); C79: Cheng et al. (1979).

Transition	24C	BZ01	L85	ZS02	F86	V94	C79
$^3P_2-^3P_2$	3.492+10	3.530+10	3.910+10	3.867+10	4.585+10	3.349+10	3.923+10
$^3P_2-^3P_1$	2.855+10	2.900+10	3.180+10	3.146+10	2.949+10	2.728+10	3.223+10
$^3P_2-^1P_1$	1.083+10	1.130+10	1.140+10	1.237+10	1.213+10	1.032+10	1.314+10
$^3P_0-^3P_1$	1.451+10	1.480+10	1.640+10	1.594+10	1.528+10	1.402+10	1.619+10
$^3P_0-^1P_1$	1.281+09	1.310+09	1.110+09	1.516+09			1.626+09
$^3P_1-^3P_2$	9.383+09	9.530+09	1.060+10	1.036+10	9.828+09		1.060+10
$^3P_1-^3P_1$	1.133+10	1.150+10	1.270+10	1.256+10	1.176+10	1.092+10	1.283+10
$^3P_1-^3P_0$	5.445+10	5.520+10	6.070+10	6.034+10	5.657+10	5.218+10	6.160+10
$^3P_1-^1P_1$	8.436+08	8.820+08	9.510+08	8.902+08			1.003+09
$^1D_2-^3P_2$	1.935+09	2.040+09	2.170+09	2.142+09	2.201+09	1.887+09	2.286+09
$^1D_2-^3P_1$	1.685+07	1.690+07	2.780+07	3.166+06		2.429+07	5.150+06
$^1D_2-^1P_1$	1.363+11	1.380+11	1.500+11	1.502+11	1.401+11	1.317+11	1.544+11
$^1S_0-^3P_1$	6.364+08	6.610+08	6.520+08	7.628+08		5.864+08	8.227+08
$^1S_0-^1P_1$	9.798+09	9.890+09	1.080+10	1.058+10	1.105+10	9.748+09	1.116+10
$^3P_1-^1S_0$	1.026+10	1.070+10	1.170+10	1.110+10		9.834+09	1.249+10
$^1P_1-^1S_0$	1.403+11	1.420+11	1.590+11	1.602+11	1.432+11	1.354+11	1.681+11

Table 12. Comparison of measured and calculated A values for the 4−9 and 5−9 transitions in Si VII. Wavelengths are calculated from observed energy levels from Edlen (1983). The measured A value was obtained from the absorption oscillator strength measured by Flaig & Schartner (1985) using the wavelengths listed.

Transition		Wvl. (Å)	f_{obs}	A_{obs}	24C	TFF02	V94	ZS02	C79
4−9	$^1D_2-^1P_1$	217.83	0.149	3.49+10	4.72+10	4.38+10	4.35+10	5.62+10	6.12+10
5−9	$^1S_0-^1P_1$	246.12	0.085	3.12+9	3.01+9	2.90+9	2.92+9	3.82+9	4.30+9

less abundant ions (P, Cl, K, Ti, Cr, Mn, Co). The present data will be included in the next release of the CHIANTI database.

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