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Transition probabilities for forbidden lines of Fe III*

P. Quinet

Laboratoire SIMPA (EP 99 du CNRS), Université de Rennes I, 35042 Rennes Cedex, France

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Abstract. — Radiative transition probabilities have been calculated for states within the $3d^6$ configuration of Fe III. Magnetic dipole (M1) and electric quadrupole (E2) transition probabilities have been obtained using average energies, electrostatic and spin-orbit integrals adjusted so as to fit the observed energy levels. The most important configuration interaction (CI) and relativistic effects were included explicitly in the calculations, using the relativistic Hartree-Fock (HFR) method due to Cowan. The present work represents a refinement of previous monoconfigurational calculations of transition probabilities for forbidden lines of astrophysical interest in Fe III.

Key words: atomic data, Fe III, radiative transition probabilities

1. Introduction

Due to its astrophysical importance, doubly ionized iron has attracted great interest in the past. The spectrum of Fe III has been extensively analyzed by Bowen (1937), Green (1939), Edlén & Swings (1942) and by Glad (1956). More recently, about 3200 lines, of which more than 1500 were new, have been observed as transitions between levels of the $3d^6$, $3d^5 4s$ and $3d^5 4p$ configurations by Ekberg (1993). In this work, 29 new levels were found in the three lowest configurations of Fe III and theoretical calculations were made to obtain transition probabilities for the observed transitions. Prior to the work of Ekberg, calculated transition probabilities in Fe III have been compiled by Fawcett (1989) and Kurucz (1990). However, all these studies concern only allowed electric dipole lines without consideration of forbidden transitions.

Forbidden lines of doubly ionized iron were first identified in the spectrum of *RY Scuti* by Edlén & Swings (1939). Since these observations, such lines have been observed in many astrophysical objects like novae, peculiar stars and planetary nebulae (see e.g. Bowen 1960; Garstang et al. 1978; Mendoza 1983). Up to now, only the transition probabilities calculated by Garstang (1957) were available for forbidden lines in Fe III. These calculations were performed in intermediate coupling but without consideration of configuration interaction effects. Garstang suggested that the strengths of his published stronger lines should be accurate to within a factor of two, the weaker lines being affected by larger uncertainties. Later, these results were used by Garstang et al. (1978) to calculate emissivities for some forbidden lines of Fe III and to estimate the iron abundances in the Orion Nebula, NGC 6720, NGC 7009 and NGC 7662 using the intensities measured by Kaler (1976). Critical compilations for forbidden transition probabilities in Fe III based on Garstang's calculations have also been published by Smith & Wiese (1973) and Fuhr et al. (1988).

Since accurate information about forbidden line strengths is necessary for the interpretation of the astrophysical spectra, we have undertaken the calculation of transition probabilities for all the magnetic dipole (M1) and electric quadrupole (E2) transitions within the $3d^6$ configuration of Fe III. The present work represents an extension to the transition probability determination of forbidden lines of astrophysical interest in Fe III and a refinement of previous monoconfigurational calculations.

2. Calculations

The method used in this study has been described previously (see e.g. Biémont et al. 1992, 1995) and the details will not be repeated here. The radial wavefunctions were generated using the approximately relativistic Hartree-Fock (HFR) method due to Cowan & Griffin (1976) with the computer codes written by Cowan (1981). Configuration interaction (CI) was retained among the configurations $3s^2 3p^6 3d^6$, $3s^2 3p^6 3d^5 4s$, $3s^2 3p^6 3d^5 4d$, $3s^2 3p^6 3d^4 4s^2$, $3s^2 3p^6 3d^4 4p^2$ and $3s 3p^6 3d^7$.

The influence of CI is different for M1 and E2 transition probabilities. In the M1 case, there is only an angular and no radial dependence so that effective parameters are well suited since they allow for the determination of the wavefunction for each level in terms of basis functions

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[*] The complete Table 3 is available in electronic form at the CDS via anonymous ftp 130.79.128.5

with well defined SLJ properties but with undefined radial wavefunctions (Trees 1951a, b; Racah 1952). In contrast, the E2 probabilities depend on the radial as well as the angular part of the basis states. However, since the E2 transition operator is a single-particle operator, to first order only a limited number of single-particle excitations contributes and many of these are included explicitly in the CI expansion. In particular, we were able to include the $3s3p^63d^7$ configuration corresponding to the core excitation 3s → 3d and which is expected to contribute to the oscillator strengths for the forbidden lines considered as mentioned recently by Quinet & Hansen (1995).

From the level energies measured by Ekberg (1993), the final radial parameter values were calculated using the Cowan's least-squares-fitting program. The optimization process was applied to the $3d^6$ and $3d^54s$ configurations. In the absence of CI, the $3d^6$ configuration is described by four parameters, $E_{\rm av}$, $F^2(3d, 3d)$, $F^4(3d, 3d)$ and ζ_{3d} while for the $3d^54s$ configuration, the five parameters $E_{\rm av}$, $F^2(3d, 3d)$, $F^4(3d, 3d)$, $G^2(3d, 4s)$ and ζ_{3d} are required. In addition to the electrostatic and spin-orbit parameters, the effective parameters α and β were included in the fit in order to allow specifically for the cumulative effects of distant configurations. The F^k, G^k and R^k integrals not optimized were arbitrarily scaled down by a factor 0.90 in agreement with a well-established practice (Cowan 1994) while ab initio values of the spin-orbit integrals, ζ, computed by the Blume-Watson method, were used without scaling.

The fitted parameter values are reported in Table 1 together with the ratios between fitted and ab initio HFR values. The root-mean-square deviation of the fit was 79 cm^{-1}. Calculated energy levels are reported in Table 2 for the $3d^6$ configuration and compared with the experimental values deduced from the work of Ekberg (1993). In agreement with previous classifications, terms having the same LS notation are distinguished by the letters a and b in increasing energy order. The eigenvector compositions obtained in our work were very close to those calculated by Ekberg (1993) and for that reason are not given in Table 2.

Table 1. Fitted parameters (in cm^{-1}) used in the calculations. The ratios between fitted values and ab initio HFR values are also indicated

Configuration	Parameter	Fitted value	Ratio
$3d^6$	$E_{\rm av}$	31223.	
	$F^2(3d,3d)$	74774.	0.8455
	$F^4(3d,3d)$	45986.	0.8367
	α	22.	
	β	716.	
	ζ_{3d}	419.	1.0000
$3d^54s$	$E_{\rm av}$	87178.	
	$F^2(3d,3d)$	79312.	0.8296
	$F^4(3d,3d)$	49167.	0.8230
	$G^2(3d,4s)$	9660.	0.8941
	α	81.	
	β	10.	
	ζ_{3d}	466.	1.0000

Table 2. Observed and calculated energy levels within the $3d^6$ configuration of Fe III. Values are given in cm^{-1}

Term	J	E_{obs} [a]	E_{calc}	ΔE [b]
^{5}D	4	0.	0.	0.
	3	436.	431.	5.
	2	739.	733.	6.
	1	932.	928.	4.
	0	1027.	1023.	4.
a^{3}P	2	19404.	19308.	96.
	1	20688.	20582.	106.
	0	21208.	21120.	88.
^{3}H	6	20051.	20087.	-36.
	5	20300.	20303.	-3.
	4	20482.	20460.	22.
a^{3}F	4	21462.	21469.	-7.
	3	21699.	21697.	2.
	2	21857.	21856.	1.
^{3}G	5	24558.	24604.	-46.
	4	24941.	24979.	-38.
	3	25142.	25161.	-19.
^{1}I	6	30355.	30411.	-56.
^{3}D	3	30857.	31003.	-146.
	2	30716.	30861.	-145.
	1	30725.	30856.	-131.
a^{1}G	4	30886.	30996.	-110.
a^{1}S	0	34812.	35070.	-258.
a^{1}D	2	35803.	35609.	194.
^{1}F	3	42896.	42863.	33.
b^{3}F	4	50276.	50311.	-35.
	3	50295.	50346.	-51.
	2	50185.	50260.	-75.
b^{3}P	2	50412.	50503.	-91.
	1	49577.	49667.	-90.
	0	49149.	49262.	-113.
b^{1}G	4	57221.	57141.	80.
b^{1}D	2	77044.	76811.	233.
b^{1}S	0	-	98153.	-

[a] Ekberg (1993)
[b] $\Delta E = E_{obs} - E_{calc}$

3. Results

The computed Einstein-coefficients, A_{ki}, are reported in Table 3 for magnetic dipole (M1) and electric quadrupole (E2) transitions within the $3d^6$ configuration of Fe III. All the calculations have been carried out using the calculated energy intervals, but the use of experimental energy differences would only produce a marginal change in the final results.

Some of the transitions considered in the present work are likely to be affected by cancellation effects in forming the radial integrals. For these transitions (starred in Table 3), the cancellation factor (CF) as defined by Cowan (1970) is smaller than 0.01 indicating that the

Table 3. Radiative transition probabilities, A_{ki} in s^{-1}, for magnetic dipole (M1) and electric quadrupole (E2) lines within the 3d^6 configuration of Fe III. A(B) stands for A.10^B. Wavelengths are given in air above 2000 Å and in vacuum below 2000 Å

Multiplet	J-J'	λ(Å)^a	M1	E2
^{5}D-a^{3}P	3-2	5270.46	4.16(-1)	9.96(-5)
	2-1	5011.33	5.43(-1)	1.27(-4)
	1-2	5412.06	3.88(-2)	2.46(-5)
	1-0	4930.64	7.03(-1)	-
	0-1	5084.85	9.27(-2)	-
^{5}D-a^{3}F	4-4	4658.17	4.50(-1)	1.31(-4)
	4-3	4607.12	4.16(-2)	4.69(-5)
	3-4	4754.72	8.36(-2)	4.68(-5)
	3-3	4701.55	2.46(-1)	1.15(-5)
	3-2	4667.02	2.66(-2)	1.45(-5)
	2-3	4769.46	8.50(-2)	3.77(-5)
	2-2	4733.93	9.76(-2)	3.10(-8)*
	1-2	4777.71	4.74(-2)	1.92(-5)
^{5}D-^{3}D	4-3	3239.79	2.16(-1)	9.34(-4)
	3-3	3286.20	6.06(-2)*	4.66(-4)
	3-2	3301.57	2.72(-2)	2.64(-5)
	2-3	3319.23	4.39(-2)	8.64(-7)*
	2-2	3334.92	1.03(-1)	3.44(-4)
	1-2	3356.59	8.84(-2)	1.85(-6)*
	1-1	3355.50	1.35(-1)	2.52(-4)
	0-1	3366.22	1.19(-1)	-
^{5}D-b^{3}F	4-4	1989.03	1.01(-1)*	9.60(-3)
	4-3	1988.27	8.46(-3)*	2.50(-3)
	3-4	2005.77	2.37(-2)	8.21(-4)
	3-3	2005.00	5.99(-2)*	1.93(-3)
	3-2	2009.45	5.34(-3)*	1.08(-3)
	2-3	2017.25	2.44(-2)	2.26(-6)*
	2-2	2021.75	2.52(-2)	7.48(-4)
	1-2	2029.70	1.39(-2)	5.40(-4)
^{5}D-b^{3}P	3-2	2000.32	2.62(-1)	6.04(-3)
	3-1	2034.31	-	3.87(-3)
	2-1	2046.92	3.63(-1)	1.06(-2)
	2-0	2065.00	-	3.03(-2)
	1-2	2020.38	1.93(-2)*	3.80(-3)
	1-1	2055.06	1.24(-4)*	9.90(-3)
	1-0	2073.29	4.73(-1)	-
	0-2	2024.27	-	3.54(-3)
	0-1	2059.08	5.33(-2)*	-
a^{3}P-^{3}D	2-3	8728.84	4.87(-2)	5.36(-4)
	2-2	8838.14	5.50(-2)	5.08(-4)
	2-1	8830.60	1.57(-2)	2.29(-4)
	1-1	9959.85	6.33(-2)	2.87(-4)
	0-1	10503.99	1.75(-2)	-
a^{3}P-a^{1}S	2-0	6488.53	-	3.84(-4)
	1-0	7078.22	1.19(+0)	-
a^{3}P-a^{1}D	2-2	6096.32	9.00(-2)	1.69(-5)*
	1-2	6614.03	3.20(-2)	4.14(-5)
a^{3}P-b^{3}P	2-2	3224.10	9.22(-5)*	5.50(-1)
	2-1	3313.31	3.00(-2)*	1.24(+0)
	2-0	3360.93	-	1.69(+0)
	1-2	3363.33	9.78(-3)*	6.46(-1)
	1-1	3460.53	3.06(-4)*	3.77(-1)
	1-0	3512.51	3.14(-2)*	-
	0-2	3423.22	-	2.68(-1)
a^{3}P-b^{3}F	2-4	3238.28	-	2.80(-1)
	2-3	3236.29	2.10(-5)*	8.46(-2)
	2-2	3247.88	2.24(-4)*	1.83(-2)
	1-3	3376.60	-	1.63(-1)
	1-2	3389.22	9.94(-5)*	1.00(-1)
	0-2	3450.04	-	1.08(-1)
a^{3}P-b^{1}D	2-2	1734.90	3.50(-2)*	5.40(-2)
	1-2	1774.41	1.52(-2)	6.38(-2)
	0-2	1790.93	-	7.44(-3)*
a^{3}P-b^{1}S	2-0	(1268.3)	-	3.88(-2)
	1-0	(1289.1)	2.07(-1)	-
^{3}H-^{3}G	6-5	22180.67	3.37(-2)	1.05(-4)
	5-5	23479.18	2.44(-2)	1.22(-5)
	4-4	22418.57	2.22(-2)*	1.78(-5)
	4-3	21451.44	3.73(-2)	1.17(-4)
^{3}H-^{1}I	6-6	9701.87	8.54(-2)*	3.06(-6)
	5-6	9942.38	5.65(-2)	7.42(-7)
^{3}H-a^{1}G	5-4	9444.12	1.82(-1)	1.19(-5)
	4-4	9608.66	7.51(-2)*	9.42(-6)
^{3}H-b^{3}F	6-4	3307.59	-	2.06(+0)
	5-4	3335.10	6.07(-4)	7.77(-2)
	5-3	3332.98	-	2.04(+0)
	4-4	3355.39	5.77(-4)*	5.97(-3)
	4-3	3353.24	6.73(-4)*	1.50(-1)
	4-2	3365.69	-	2.14(+0)
^{3}H-b^{1}G	5-4	2707.71	7.63(-2)	2.09(-5)*
	4-4	2721.07	5.98(-2)*	4.69(-3)
^{3}H-b^{1}D	4-2	1767.94	-	8.62(-2)
a^{3}F-^{3}G	4-5	32284.89	1.72(-2)	1.36(-6)
	4-4	28733.74	2.74(-2)*	2.10(-7)
	3-3	29040.23	2.87(-2)	7.06(-7)
	2-3	30430.88	1.81(-2)	1.64(-6)
a^{3}F-a^{1}G	4-4	10607.92	2.02(-1)	7.70(-8)*
	3-4	10882.47	1.03(-1)	1.07(-6)

corresponding transition probability must be considered with some care.

The effects of configurations not included explicitely in our physical model due to computer memory limitations were estimated in separate HFR calculations. More precisely, the configurations 3d^{4}4d^2 and 3d^{4}4s4d were investigated separately. By comparing a three-configuration calculation (including 3d^6, 3d^{5}4s and 3d^{4}4s^2) with four-configuration calculations (adding 3d^{4}4d^2 and 3d^{4}4s4d), the effect on the f values of the latter two configurations was estimated and found negligible. Indeed, the mean difference was only Δ =0.009 and 0.006 dex respectively (for

Table 3. continued

Multiplet	J-J'	λ(Å)^a	M1	E2
a^{3}F-^{3}D	4-3	10640.31	6.60(-3)	3.66(-3)
	4-2	10803.17	-	1.69(-3)
	3-3	10916.57	4.74(-3)*	1.05(-3)
	3-2	11088.06	2.12(-3)	1.92(-3)
	3-1	11076.19	-	2.29(-3)
	2-3	11107.38	1.20(-3)	1.03(-4)
	2-2	11284.97	1.47(-3)	1.31(-3)
	2-1	11272.68	3.57(-3)	2.91(-3)
a^{3}F-a^{1}D	3-2	7088.46	2.24(-1)	2.66(-4)
	2-2	7168.42	1.20(-1)	3.34(-6)*
a^{3}F-b^{3}F	4-4	3469.52	7.10(-3)*	9.19(-1)
	4-3	3467.23	7.84(-2)*	7.79(-2)
	4-2	3480.54	-	5.46(-2)
	3-4	3498.39	5.59(-2)*	1.80(-1)
	3-3	3496.06	2.69(-3)*	6.30(-1)
	3-2	3509.59	8.16(-2)*	1.60(-1)
	2-4	3517.76	-	7.42(-3)
	2-3	3515.40	4.61(-2)*	2.07(-1)
	2-2	3529.08	1.81(-4)*	6.56(-1)
a^{3}F-b^{1}G	4-4	2795.65	1.20(-1)*	1.39(-5)*
	3-4	2814.36	4.42(-2)	6.29(-4)
a^{3}F-b^{3}P	4-2	3453.24	-	1.64(-1)
	3-2	3481.84	3.22(-4)*	4.92(-2)
	3-1	3586.11	-	1.21(-1)
	2-2	3501.02	5.30(-5)*	5.24(-3)
	2-1	3606.47	2.71(-4)	6.60(-2)
	2-0	3662.97	-	1.71(-1)
a^{3}F-b^{1}D	4-2	1799.12	-	4.52(-1)
	3-2	1806.85	4.74(-3)	1.17(-2)
	2-2	1812.00	9.28(-4)*	1.06(-1)
a^{3}F-b^{1}S	2-0	(1310.7)	-	3.83(-1)
^{3}G-b^{3}F	5-4	3887.29	1.18(-1)	7.72(-1)
	5-3	3884.41	-	3.46(-2)
	4-4	3946.01	7.99(-2)*	4.40(-2)
	4-3	3943.04	5.16(-3)*	7.00(-1)
	4-2	3960.26	-	6.82(-2)
	3-4	3977.57	4.20(-3)*	5.94(-4)
	3-3	3974.56	1.22(-1)*	7.61(-2)
	3-2	3992.06	8.28(-2)	7.38(-1)
^{3}G-^{1}F	5-3	5451.72	-	3.30(-4)
	4-3	5567.92	9.54(-2)	9.21(-4)
	3-3	5630.97	4.87(-2)	2.93(-4)
^{3}G-b^{1}G	5-4	3060.70	1.77(-1)	5.08(-3)
	4-4	3096.99	1.82(-2)*	6.32(-4)
	3-4	3116.40	1.82(-1)	8.80(-4)
^{3}G-b^{1}D	4-2	1919.25	-	1.28(-1)
	3-2	1926.69	2.92(-6)*	3.48(-2)
^{1}I-b^{1}G	6-4	3721.19	-	2.10(+0)
^{3}D-a^{1}D	3-2	20214.19	3.08(-2)	1.06(-6)
	2-2	19651.39	5.82(-3)*	9.40(-7)
	1-2	19688.77	3.24(-2)	2.38(-7)
^{3}D-^{1}F	3-3	8304.28	5.84(-2)	1.90(-5)
	2-3	8207.71	3.36(-2)	1.69(-4)
^{3}D-b^{3}P	3-2	5112.52	7.60(-2)	2.58(-1)
	3-1	5340.54	-	1.94(-1)
	2-2	5075.76	3.04(-2)*	1.75(-1)
	2-1	5300.43	1.36(-3)*	2.59(-2)
	2-0	5423.37	-	3.59(-1)
	1-2	5078.25	1.49(-2)	4.84(-2)
	1-1	5303.15	7.63(-2)	1.78(-1)
	1-0	5426.22	7.25(-2)	-
^{3}D-b^{3}F	3-4	5148.29	9.80(-2)	6.63(-3)
	3-3	5143.24	1.27(-1)	1.04(-3)
	3-2	5172.58	1.25(-2)	1.23(-5)
	2-2	5134.95	1.61(-1)	2.34(-3)
	1-2	5137.50	8.80(-2)	3.76(-3)
^{3}D-b^{1}D	3-2	2164.42	2.78(-1)	8.12(-2)
	2-2	2157.80	4.40(-2)*	2.10(-1)
	1-2	2158.25	2.58(-1)	1.60(-2)
^{3}D-b^{1}S	2-0	(1486.1)	-	2.63(+0)
	1-0	(1485.9)	1.85(-3)	-
a^{1}G-b^{1}G	4-4	3796.15	1.38(-4)*	2.21(-1)
a^{1}G-b^{1}D	4-2	2165.77	-	1.53(+1)
a^{1}S-b^{3}P	0-2	6408.51	-	1.95(-4)
	0-1	6770.87	8.77(-2)	-
a^{1}S-b^{1}D	0-2	2367.11	-	1.45(+0)
a^{1}D-b^{3}P	2-2	6843.35	1.35(-1)	6.22(-4)
	2-1	7258.14	5.73(-2)	2.88(-4)
	2-0	7490.66	-	1.83(-3)
a^{1}D-b^{3}F	2-4	6907.58	-	2.31(-4)
	2-3	6898.50	3.19(-2)	2.59(-4)
	2-2	6951.38	1.58(-2)*	1.85(-5)
a^{1}D-b^{1}G	2-4	4667.66	-	3.12(-2)
a^{1}D-b^{1}D	2-2	2424.00	1.93(-3)*	6.62(+0)
a^{1}D-b^{1}S	2-0	(1598.9)	-	1.22(+2)
^{1}F-b^{3}F	3-4	13546.72	5.87(-2)	1.81(-5)
	3-3	13511.85	6.26(-3)	1.37(-6)
	3-2	13716.21	1.02(-1)	3.20(-6)
^{1}F-b^{1}G	3-4	6978.87	1.20(-3)	6.31(-2)

both M1 and E2 contributions) if we except the transitions affected by cancellation effects and the transitions involving the state b^{1}D. When adding the 3d^{5}5s and 3d^{5}5d configurations to the three-configuration expansion, the mean difference was then $\Delta = 0.005$ dex for M1 transitions and 0.043 dex for E2 transitions. The configurations with a single 3s electron, i.e. 3s3p^{6}3d^{6}4s and 3s3p^{6}3d^{6}4d, were suspected to affect the energies and for that reason were also investigated. The inclusion of these two configurations was found to affect the gf values for all the transitions within 3d^6 by less than 0.002 dex and 0.014 dex for M1 and E2 contributions respectively. Finally, the effect of the 3p^{5}3d^{6}4p configuration corresponding to the single-particle excitation 3p → 4p was estimated. In this case, the mean difference was 0.005 dex for both M1 and E2 transitions. Consequently, the set of configurations listed in Sect. 2 is expected to take into account the most important configuration interaction effects. Moreover, it is

Table 3. continued

Multiplet	J-J′	λ(Å)[a]	M1	E2
^{1}F-b^{1}D	3-2	2927.53	1.72(-3)	1.03(+0)
b^{3}P-b^{1}D	2-2	3753.70	4.80(-2)	3.66(-3)
	1-2	3639.60	1.65(-2)	7.40(-6)*
b^{3}P-b^{1}S	2-0	(2098.0)	-	5.15(-2)
	1-0	(2061.8)	1.67(+0)	-
b^{3}F-b^{1}G	4-4	14394.56	2.64(-2)	1.03(-6)
	3-4	14434.15	1.53(-2)	2.01(-5)
b^{3}F-b^{1}D	4-2	3734.65	-	3.44(-3)
	3-2	3737.31	6.54(-2)	3.90(-4)
	2-2	3721.97	3.48(-2)	2.68(-4)
b^{1}G-b^{1}D	4-2	5043.11	-	5.38(-1)
b^{1}D-b^{1}S	2-0	(4684.3)	-	1.97(+0)

[a] Deduced from the observed energy levels (Ekberg 1993). Values between parentheses are calculated HFR wavelengths.
* Cancellation effects present (see text).

well established that the neglect of some configurations is partly overcome by scaling down the Slater integrals and by fitting the calculated energy levels to the observed values.

Among the transitions reported in Table 3, are several in which electric quadrupole radiation is stronger than the magnetic dipole radiation. This is the case in particular for the a^{3}P$-$b^{3}P, a^{3}P$-$b^{3}F, a^{3}P$-$b^{1}D, ^{3}H$-$b^{3}F, a^{3}F$-$b^{3}P, a^{3}F$-$b^{1}D, ^{3}G$-$b^{1}D, ^{3}D$-$b^{3}P, a^{1}G$-$b^{1}G, a^{1}D$-^1$F, a^{1}D$-$b^{1}D, ^{1}F$-$b^{1}G and ^{1}F$-$b^{1}D transitions. For the remaining lines, magnetic dipole radiation predominates.

A very limited number of transition probabilities has been reported previously for forbidden lines in Fe III. To our knowledge, only the results obtained by Garstang (1957) who performed intermediate coupling calculations have been published. In general, for the M1 transitions, these results agree within 10$-$30% with the transition probabilities obtained in the present work if we except some transitions affected by cancellation effects (i.e. ^{5}D$_2-$a^{3}P$_2$, ^{5}D$_1-$a^{3}P$_1$, ^{5}D$_4-^3$G$_4$, ^{5}D$_4-$a^{1}G$_4$, a^{3}P$_1-^3$D$_2$, a^{3}F$_4-^3$G$_3$, a^{3}F$_3-^3$G$_4$, a^{3}F$_3-^3$D$_2$, a^{3}F$_{2,3,4}-^1$F$_3$, ^{3}G$_4-$a^{1}G$_4$, ^{3}G$_{3,4}-^3$D$_{2,3}$) and the ^{5}D$_3-$ ^{3}G$_4$, ^{5}D$_{2,3}-^3$G$_3$, ^{3}H$_5-^3$G$_4$, ^{3}G$_3-$ a^{1}G$_4$, ^{3}D$_{1,2,3}-$a^{1}D$_2$ and ^{3}D$_1-$a^{1}S$_0$ transitions for which larger discrepancies are observed. Exceptions occur also for the very weak ^{3}D$_1-^3$D$_2$ and a^{1}G$_4-^3$D$_3$ transitions and for the transitions within the ^{3}H multiplet characterized by small energy differences. However, for the most intense M1 transitions, the two scales differ by at most a few percent. For the E2 contributions, large discrepancies are observed for a number of transitions and they can reach a factor of two in many cases. However, as mentioned above, these transitions are more sensitive than the M1 contributions to correlation effects and Garstang's results were obtained in intermediate coupling but without consideration of configuration interaction effects. Therefore, the present data are expected to be more accurate.

Garstang (1957) published also forbidden transition probabilities for multiplets corresponding to the nine highest energy levels within the 3d^6 configuration. For M1 transitions, the general agreement is good (within 20%) between Garstang's results and our calculated transition probabilities if we except some lines affected by cancellation and the ^{1}F$-$b^{3}P and a^{3}P$-$b^{1}S transitions for which the discrepancies can reach a factor of two. As expected, for E2 transitions, the agreement between both sets of results is rather poor even for the strongest lines.

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