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Fe^+ column density and line opacities of the UV2 multiplet of Fe II in laboratory and peculiar stellar sources⋆

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Abstract. The Self-Absorption Curve method has been applied to the UV2 multiplet $a^6D-z^6F^o$ of Fe II observed in the laboratory and in emission–line stars. For the laboratory observations line opacities of this multiplet were obtained using various sets of atomic data. The best fit is obtained using data by Bergeson et al. (1996), which provide line opacities that are in remarkable agreement with results by Kastner (1999a), derived using independent methods. A value of 7.3×10^{12} cm^{-2} for the Fe^+ column density is derived for the laboratory source, and lower limits of 2.1×10^{15} and $\sim2\times10^{17}$ cm^{-2} are obtained for the peculiar stars KQ Pup and RR Tel, respectively.

Key words: atomic data – line: formation – methods: data analysis – stars: emission-line, Be – stars: individual: KQ Pup – stars: individual: RR Tel

1. Introduction

For over a decade we have been investigating the physical conditions in the atmospheric envelopes of emission line stars using the method of the Self–Absorption Curve (SAC), described by Friedjung & Muratorio (1987) and Baratta et al. (1998). In applying this analysis to the study of the Fe II emission lines in various peculiar stars, we were often faced with a noticeable dispersion of the experimental points, that could be ascribed to uncertainties in the gf–values, and which eventually prevent the evaluation of the effectiveness of this analysis.

Thus, it would be desirable to see to what extent errors in the estimated gf–values can influence the derived opacities and abundances, and in particular the population of individual levels, which, in peculiar astrophysical objects, can deviate considerably from that of LTE, for instance as a result of fluorescence processes.

For this purpose, it would be interesting to study a laboratory spectrum that shows self–absorption, and to use it to check the accuracy of the atomic data. A good example of this kind is represented by the Fe II laboratory spectrum provided by Thorne et al. (1987), where Kastner (1999a) has found lines that are self–absorbed. Following the suggestion of Kastner (1999b), we have applied the SAC method to the 13 ultraviolet Fe II lines of multiplet UV2 ($a^6D - z^6F^o$), accurately measured by Thorne et al. We then compared the results of our analysis of the same lines in two stellar objects, KQ Pup and RR Tel. We were able to derive iron column density and line opacities that show consistency for a selected list of atomic data, and we thought it, therefore, worthwhile to bring here our results.

2. Theoretical SAC

Following Baratta et al. (1998), for the analysis of the observational data we shall adopt the normalized emission line flux: $F_n = F\lambda^3/gf$. The graphs of the logarithm of this quantity versus the logarithm of $gf\lambda$ is the observational Self–Absorption Curve (SAC), which puts in evidence the self–absorption effects. The normalized flux of a line crossing a homogeneous slab of matter with opacity $\tau(\lambda)$ constant in λ is reduced by a factor $\dfrac{1-e^{-\tau}}{\tau}$. The same term applies in the simplified case discussed by Friedjung & Muratorio (1987) of a line with a rectangular absorption profile, where $\tau(\lambda)$ is equal to a constant value τ_r in the interval $\lambda_o \pm \delta\lambda_r$. The corresponding theoretical SAC is:

$$Q(\tau_r) = log\ \frac{1-e^{-\tau_r}}{\tau_r} \tag{1}$$

(here and in the following we shall use decimal logarithms). $Q(\tau_r)$ is equal to -0.1992 for $log\ \tau_r = 0$, and approximates $-log\ \tau_r$ for very large values of τ_r (in practice for $log\ \tau_r > 0.6$).

In a more realistic model, the lines have a Gaussian profile $\tau(\lambda) = \dfrac{\tau_g}{\sqrt{\pi}}\ e^{-L^2}$, where τ_g is the integrated line opacity and $L = \dfrac{(\lambda-\lambda_o)\,c}{\lambda_g\,v_d}$, which yields for the theoretical SAC the expression:

$$Q(\tau_g) = log\ \left(\int_{-\infty}^{+\infty} \frac{1-e^{-\tau}}{\tau_g}\ dL\right) \tag{2}$$

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⋆ Based on observations made with the *International Ultraviolet* retrieved from the IUE archive.

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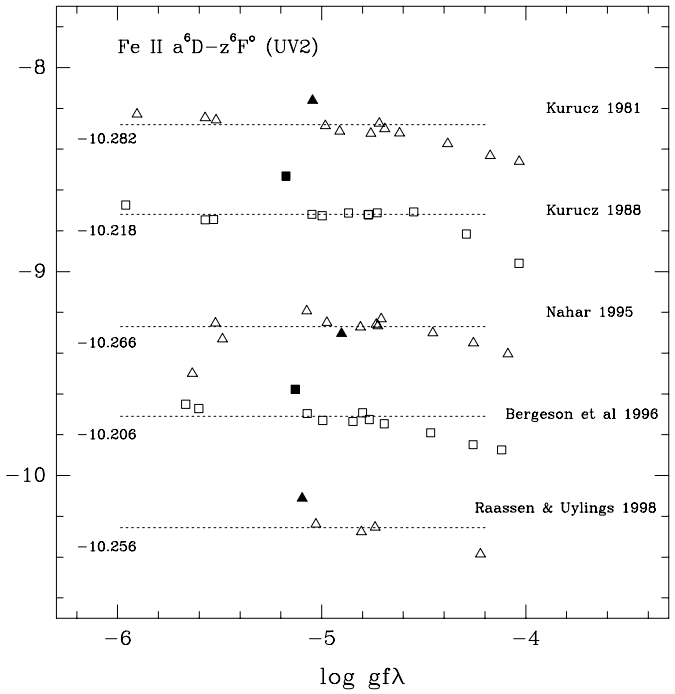

Fig. 1. The laboratory intensity of the Fe II ultraviolet multiplet $a^6D - z^6F^o$ (from Thorne et al. 1987). Plots on the [$log\ gf\lambda$, $log\ F\lambda^3/gf$] plane for various sets of atomic data: Kurucz (1981), Kurucz (1988), Nahar (1995), Bergeson et al. (1996), and Raassen & Uylings (1998). A vertical offset of +0.5 dex was applied to the successive plots. The filled symbol refers to the 237.446 nm line (no.2 of Thorne et al. list). The horizontal lines mark the mean ordinate (labeled on the left); the most deviating points have been excluded from the mean.

$Q(\tau_g)$ becomes a straight line with the classical -1 slope for $log\ \tau_g > \ \sim 3$, and the bending of the curve near $log\ \tau_g = 0$ is much smoother than in the rectangular profile case discussed above, as is also shown in Fig. 2 of Friedjung & Muratorio (1987). Note also that the self–absorption effect is much lower, the $Q_g - Q_r$ difference being equal to –0.117 and –0.778 at $log\ \tau$ = 0 and 6, respectively. The overlapping of the two curves for small τ can be obtained from a horizontal shift of about 0.4 dex, corresponding to the term $log\ \sqrt{2\pi}$, which originates from the different definitions of the line profile. Vacuum wavelengths will be used throughout the paper.

3. Application of SAC to laboratory sources

For this work we shall make use of the 13 ultraviolet Fe II lines of multiplet UV2 ($a^6D - z^6F^o$) from a glow–discharge source at a temperature of $2500 \pm 80^\circ K$, with a 2 Torr pressure that Thorne et al. (1987) observed using a Fourier–Transform spectrograph. They provided a very accurate measure of the line profiles, and also gave the line relative intensities, integrated over the line profile, uncorrected for the instrument transmission. However, the FTS response varies only slowly with wavenumber, and the lines here considered are so close to each others, that one would expect the measured relative fluxes to be accurate enough for our purposes. Thorne et al. also noted that the two strongest lines, 238.277 and 239.636 nm, are significantly self–absorbed, as these lines are flattened on the top, and have an anomalously large FWHM. The lines will be numbered following Thorne et al.

Table 1. Logarithm of normalized emission line fluxes

n	λ(vac.)	flux	Ku81	Ku88	Na95	Be96	RU98
2	237.446	1959	-10.162	-10.032	-10.303	-10.077	-10.111
1	238.277	10000	-10.460	-10.459	-10.404	-10.374	
6	238.379	228	-10.229	-10.174	-10.500		
5	238.936	3131	-10.274	-10.220	-10.259	-10.192	
9	239.615	463	-10.246	-10.246	-10.330	-10.151	
4	239.636	7517	-10.432	-10.316	-10.350	-10.348	-10.384
8	239.997	3080	-10.300	-10.221	-10.267	-10.225	-10.253
12	240.516	504	-10.257	-10.245	-10.254	-10.172	
7	240.562	5238	-10.374	-10.208	-10.301	-10.290	
11	240.739	2472	-10.323	-10.213	-10.272	-10.235	-10.276
10	241.125	3403	-10.321	-10.212	-10.231	-10.246	
14	241.180	1767	-10.312	-10.226	-10.250	-10.229	
13	241.405	1595	-10.284	-10.219	-10.193	-10.196	-10.238

Notes to the table: The table gives in the third column the relative laboratory intensities F measured by Thorne et al. (1987), and in Columns 4–8 the logarithm of the quantities $F\lambda^3/gf$, where the f–values are taken, for the successive columns, from: Kurucz (1981), Kurucz (1988), Nahar (1995), Bergeson et al. (1996), and Raassen & Uylings (1998). The lines are numbered according to Thorne et al.

We have plotted in Fig. 1 the laboratory intensities on the [$log\ gf\lambda$, $log\ F\lambda^3/gf$] plane using gf–values derived from various sources: Kurucz (1981), Kurucz (1988)[1], the Iron Project data (Nahar 1995), Bergeson et al. (1996), and Raassen & Uylings (1998). The logarithm of the normalized emission line fluxes from the different sets of atomic data are given in Table 1. Most of the lines lie on a nearly horizontal line, in agreement with their negligible self–absorption.

In four of these sources the J=$4\frac{1}{2}$-J=$4\frac{1}{2}$ line at 237.446 nm has a deviation of 0.2 dex (+60%) above the curve. This can be attributed to an inaccuracy either in the flux measurement, or, alternatively, to a 60% underestimate of most of the computed oscillator strengths of this line. In one case (the Iron Project) its representative point is in remarkable agreement with the observed intensity, indicating that the latter hypothesis cannot be discarded.

In Fig. 1 we draw horizontal lines fitting the optically thin lines; the λ237.446 line was excluded from the mean in three cases. The corresponding average normalized fluxes, indicated in the figure, give an idea about the small ($\pm$5%) systematic difference between the five sets of oscillator strengths here considered.

The fact that the two strongest transitions (238.277 and 239.636 nm) fall below the straight line indicates a trend that we attribute to a not negligible optical thickness of the discharge

[1] extracted from the Hannover web page (www.pmp.uni-hannover.de/projekte/kurucz/sekur.html) which is the atomic spectral line database, built from atomic datafiles from R.L. Kurucz' CD-ROM 23.

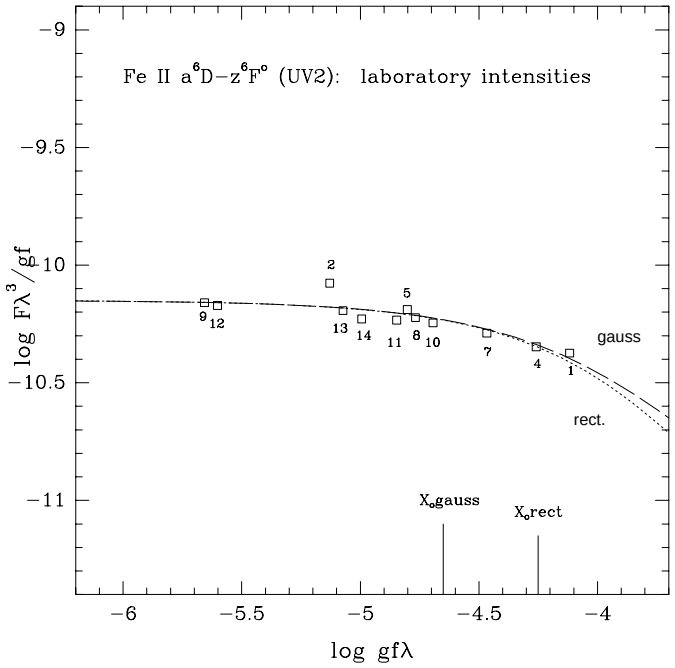

Fig. 2. Best fit of the laboratory intensities with a thin uniform slab theoretical SAC for lines with rectangular profile (dotted line) and Gaussian (solid line), as described by Eqs. (1) and (2). The abscissae corresponding to opacity equal to unity for the two SAC curves are marked. The gf–values are from Bergeson et al. (1996). Thorne et al. (1987) line numbers are indicated. The deviating point is the 237.446 nm line (no. 2), not used for the fit.

in the lamp, in agreement with by above mentioned remarks by Thorne et al. (1987).

Actually, Thorne et al. (1987) remarked that these two lines were significantly self–absorbed, as is apparent from their observed profiles (regrettably not shown in their paper). In fact these two lines (and to a lesser extent the third strongest line at 240.562 nm) are broader than the other lines.

We have fitted the data points of Fig. 1 with the theoretical SAC that we have computed for a homogeneous thin slab, for both rectangular and Gaussian line profiles, using the formulae given in Eqs. (1) and (2). As discussed by Baratta et al. (1998), the horizontal adjustment of the SAC provides the value of the opacity–fit parameter X_o which is the $log\ gf\lambda$ of a virtual line of the multiplet having opacity equal to unity. The 237.466 nm line was excluded from the fit. The best fit is found for the graph plotted using the atomic data of Bergeson et al. (1996). A good fit is also found using the data from Kurucz (1981). The plot is shown in Fig. 2. In this figure the two theoretical SAC curves practically overlap, so that it is not possible to decide which of the two provides the best fit. However, the reference abscissa X_o corresponding to unity opacity is not the same. In fact the fits provide X_o = $-4.25\pm.05$ and $-4.65\pm.05$ for a rectangular and Gaussian profile, respectively. Hence, the line centre opacity for a Gaussian profile is a factor $\sim$2.5 larger than the rectangular profile opacity, a result which derives from the different definition of τ_g and τ_r, as discussed above. The X_o values for a Gaussian profile derived for the different sets of oscillator strengths are given in the last row of Table 2.

The SAC fit adjusts the abscissa scale so that we can derive the opacity of the individual line i from its corresponding abscissa:

$$log\ \tau_g(i) = (log\ gf\lambda)_i - X_o \qquad (3)$$

The opacities of the strongest multiplet lines derived from the fit of the SAC model with a Gaussian line profile, are given in the last column of Table 2. In this table we also give the line opacities derived by fitting the graphs where other sets of oscillator strengths are used. The uncertainty of these values is that of X_o given in the table. One may notice that the line opacities obtained by using Kurucz's (1981) atomic data are in good agreement with those based on the data of Bergeson et al. (1996). The same line opacities are also derived from the accurate Raassen & Uylings (1998) data. Significantly smaller opacities are obtained, however, in the case of the more recent Kurucz' data (Kurucz 1988), and of the atomic data from the Iron Project (Nahar 1995). It should be noted here that the X_o value crucially depends on the position in the plot of the 2–3 strongest lines, so that a small difference in their oscillator strengths may result in a large difference in X_o.

In the table we give, for comparison, the line opacities derived by Kastner (1999a) from the line width (FWHM) using the escape probability method. These opacities are in good agreement with those derived here from the SAC fit using the atomic data of Kurucz (1981) and of Bergeson et al. (1996). It should be remembered that in the two cases the opacities were determined using two independent methods, based on two different sets of observational data: line widths and line intensities.

Once the line opacity is known, the ground level column density of the absorbing ion N_o can be computed using the following expression for absorption from a thin homogeneous slab and a Gaussian line profile (Baratta et al. 1998):

$$log\ \frac{N_o}{g_o} = -(log\ gf\lambda)_o + log\ v_d + 1.576\ [cgs\ units] \qquad (4)$$

where: g_o is the Fe^+ ground level statistical weight ($g_o = 30$), v_d is the thermal line broadening velocity ($log\ v_d$ = 5.16 for the laboratory source temperature of 2500°K), and $(log\ gf\lambda)_o = X_o = -4.65$ is the oscillator strength of a virtual line of the multiplet having unity opacity. At the above mentioned temperature most Fe^+ ions are in the ground state, so that $N_o \approx N(Fe^+)$. Hence: $N(Fe^+) = (7.3 \pm 0.2) \times 10^{12}$ cm^{-2}, where the error is due to the uncertainty on X_o. A 40% smaller column density is derived if the atomic data of Kurucz (1988) are used.

4. Fe II multiplet UV2 in emission line stars

The IUE satellite has provided an extensive archive of ultraviolet spectra in the above spectral region. This archive includes several peculiar objects that were luminous enough in the UV to be observed at high resolution, and with an Fe II emission line spectrum strong enough to have measurable fluxes, as, for instance, the VV Cep–type binary KQ Pup and the symbiotic nova RR Tel.

Table 2. Line opacities of the strongest lines and the corresponding fit parameters

line no	λ(vac.) (nm)	FWHM Kastner[a]	Ku81	SAC[b] Ku88	Na95	Be96
1	238.277	3.74 (.23)	3.296	2.328	2.053	3.406
4	239.636	2.49 (.16)	2.374	1.287	1.392	2.462
7	240.562	1.39 (.11)	1.469	0.710	0.881	1.526
10	241.125	0.77 (.10)	0.853	0.470	0.492	0.905
8	239.997	0.72 (.10)	0.723	0.427	0.474	0.763
5	238.936	0.64 (.10)	0.679	0.425	0.465	0.704
11	240.739	0.56 (.10)	0.619	0.340	0.389	0.636
X_o [c]		==	-4.55±.05	-4.40±.10	-4.40±.10	-4.65±.05

Notes to the table: (a) Line opacity (with standard error) derived by Kastner (1999a) from the line full width at half maximum (FWHM). (b) Line opacity from the SAC fit using a theoretical SAC for a thin uniform slab with a Gaussian line profile. The different sources for atomic data are, Ku81: Kurucz (1981), Ku88: Kurucz (1988), Na95: Nahar (1995), Be96: Bergeson et al. (1996). (c) Opacity–fit parameter for a SAC model with Gaussian line profile.

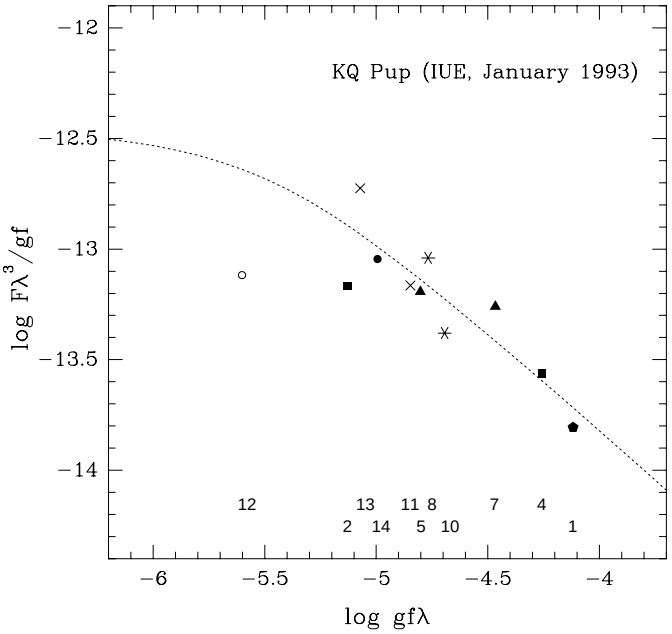

Fig. 3. SAC plot of the Fe II multiplet UV2 in the emission line star KQ Pup observed with IUE on 13 January 1993. The observational data are fitted with the Gaussian line profile theoretical SAC, which corresponds to unity opacity at $log\, gf\lambda = -6.0$ (upper limit). Thorne et al. (1987) line numbers are indicated at the bottom. Different symbols are used for lines coming from different upper levels, from $J_u=\frac{1}{2}$ to $J_u=5\frac{1}{2}$: *circles*, *crosses*, *stars*, *triangles*, *squares*, and *pentagons*. The open circle refers to the weak 240.516 nm line, not used in the fit.

Table 3. Fe II emission line fluxes in KQ Pup

n	λ(vac.)	gf	E_{lo}	E_{up}	F_{kq}	w
2	237.446	0.313 (.004)	0.000	5.222	1.6	1
1	238.277	3.20 (.04)	0.000	5.204	3.7	1
5	238.936	0.66 (.03)	0.048	5.237	3.1	1
4	239.636	2.30 (.04)	0.048	5.222	4.6	2
8	239.997	0.712 (.026)	0.083	5.249	4.7	2
12	240.516	0.104 (.010)	0.107	5.262	0.57	0
7	240.562	1.42 (.05)	0.083	5.237	5.6	2
11	240.739	0.591 (.021)	0.107	5.257	2.9	1
10	241.125	0.84 (.03)	0.107	5.249	2.5	1
14	241.180	0.420 (.004)	0.121	5.262	2.7	1
13	241.405	0.351 (.016)	0.121	5.257	4.7	2

Notes to the table: gf–values (with uncertainties) are from Bergeson et al. (1996). F_{kq}: emission line fluxes in Janaury 1993, in 10^{-12} erg cm^{-2}s^{-1}, uncorrected for interstellar extinction. E_{lo}, E_{up}: the lower and upper level energy (in eV) of the transition. w: flux uncertainty: 2: 10–20%, 1: 20–30%, 0: >30%.

4.1. KQ Pup

KQ Pup is a long period interactive binary, in which the wind of the M–supergiant component is ionized by the radiation of the hot dwarf companion (Rossi et al. 1992). The optical and ultraviolet spectrum is rich in emission lines, especially of singly ionized iron. We have measured the flux of the Fe II UV2 emission lines in the IUE long–wavelength spectra obtained in February 1979 and in January 1993. We have found that the fluxes in the latter spectrum are systematically stronger (by about +40%), in agreement with the increase of emission line excitation after the apoastron passage of the KQ Pup binary system (see Rossi et al. 1992, Viotti et al. 1998). The emission line fluxes of January 1993 are given in Table 3.

For this analysis we have used the atomic data of Bergeson et al. (1996), but in this case the large scatter of the points does not allow to put in evidence any differences among the various sets of atomic data.

The plot in Fig. 3 shows that the lines of the 1993 spectrum lie on an inclined line with a mean slope of $-0.76\pm.16$, corresponding to optically thick emission lines. The uncertain point of the line no. 12 was not considered. All the emission lines have a P Cygni absorption component which makes the measurements of their flux difficult. We recall that Muratorio et al. (1992) used in their analysis emission line fluxes corrected for the absorption.

In this case the Fe^+ column density could not be derived as it was for the laboratory measurements. However, following Baratta et al. (1998) we could set a lower limit for it. For this

purpose we have fitted the points in Fig. 3 with the theoretical SAC for a Gaussian profile, by imposing that the curve bend just to the left of the last points is shown. This curve corresponds to the value X_o = –6.0, from which, assuming in agreement with Muratorio et al. (1992) v_d=10 km s^{-1} and a mean level excitation temperature of 9000°K, a value of $\sim 2.1 \times 10^{15}$ cm^{-2} is obtained as a *lower limit* for the Fe^+ column density.

This value has to be compared with the value of $(1.1 \pm 0.5) \times 10^{18}$ cm^{-2} derived by Muratorio et al. (1992) from the SAC analysis of the IUE spectrum of KQ Pup of February 1979. This $\sim 10^3$ factor, however, can be explained by the fact that Muratorio et al. extended their analysis to weaker, higher excitation lines, whose position in the combined SAC curve was about three decades towards smaller $gf\lambda$ values with respect to the multiplet UV2 lines, as shown in Fig. 4 of Muratorio et al. (1992). (In that figure the wavelengths are expressed in Å). The difference with Muratorio et al. can further be accounted for by their different theoretical SAC model computed for an inhomogeneous emitting region, and by the spectral variation of KQ Pup from 1979 to 1993.

The standard deviation of the points from the fit (without line 12), is of 0.16 dex. As it can be noted from the comparison of Fig. 3 with Fig. 1, the dispersion in the KQ Pup data is larger than the uncertainty in the atomic data, and could be attributed to observational errors and/or to deviation from LTE of the population of the upper levels of the transitions. In order to investigate this latter point, we have indicated in Fig. 3 with different symbols the lines originating from the different z^6F^o levels: from J=$\frac{1}{2}$ to J=5$\frac{1}{2}$. It is evident in the figure that there is no systematic vertical shift among lines with different upper levels. Hence, the dispersion is mostly due to observational errors, which does not allow us to investigate details of the level population. Muratorio et al. (1992), however, have put in evidence in the IUE spectra population excesses, for instance due to fluorescence effects.

4.2. RR Tel

For the symbiotic nova RR Tel we have used the fluxes measured by Penston et al. (1983) in the IUE high resolution spectra collected during 1978–1979. The SAC plot presented in Fig. 4 shows that all the points lie on an inclined line with a mean slope of –1.06±.15. We thus conclude that, like in KQ Pup, the Fe II multiplet UV2 emission lines in RR Tel are optically thick, also in agreement with the $\sim 10^3$ opacity of the Fe II multiplet UV1 found by Penston et al. (1983). The slope is definitely larger than in KQ Pup, which, if the same SAC can be applied to both cases, would mean that in RR Tel the line opacity is at least one order of magnitude larger. This is confirmed by the SAC fit shown in Fig. 4. The curve in the figure corresponds to the minimum line opacity, and provides an upper limit to X_o of about –8.0. Assuming the same v_d and level excitation temperature of KQ Pup, we get a lower limit to the Fe^+ column density of $\sim 2 \times 10^{17}$ cm^{-2}. The standard deviation of the data from the fit is rather low, about 0.13 dex, confirming the good quality of these early IUE measurements. Also in this case we find no systematic vertical shift among lines with different upper levels, suggesting that they are in statistical equilibrium.

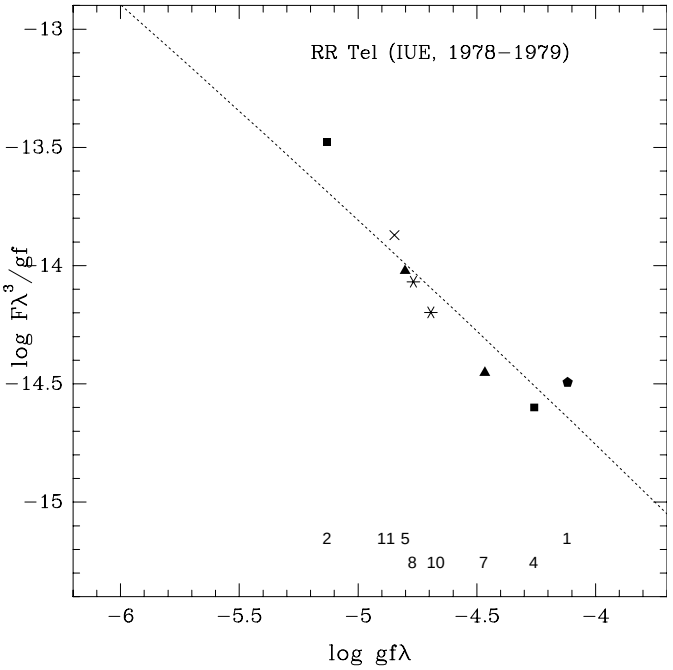

Fig. 4. Same as Fig. 3, for the symbiotic nova RR Tel (IUE, 1978–1979). The SAC fit gives the upper limit to unity opacity at $log\ gf\lambda = -8.0$.

5. Conclusion

Our SAC analysis of multiplet UV2 of Fe II in laboratory and stellar sources leads to the following results:

1. Previously the SAC method was applied only to astrophysical sources. Here we have shown that it can be successfully applied also to a laboratory source.
2. We have also applied it to two stars and put in evidence a large optical thickness, in agreement with previous researchs.
3. In a check for consistency among the atomic data that are usually used, we found that in the case of multiplet UV2 of Fe II those of Bergeson et al. (1996) and of Kurucz (1981) give the best fit.
4. A final confirmation of our approach is the good fit with the results of Kastner (1999a) which have been obtained using an independent method.

We conclude by pointing out the importance of high signal–to–noise data from emission–line stellar objects for the evaluation of refined details such as deviations of the level population from equilibrium. Further comparison involving other mutliplets observed in stellar spectra will be undertaken in future work. Finally, an accurate data set, obtained with a laboratory source with optical thickness larger than that used here, would be very useful to better trace the self–absorption curve at optical opacities near unity.

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References

Baratta G.B., Friedjung M., Muratorio G., Rossi C., Viotti R., 1998, The Self Absorption Curve Method, A Users' Manual. IAS Internal Report, December 1998

Bergeson S.D., Mullman K.L., Wickliffe M.E., et al., 1996, ApJ 464, 1044

Friedjung M., Muratorio G., 1987, A&A 188, 100

Kastner S.O., 1999a, Physics Letters A, 254, 279

Kastner S.O., 1999b, A&A 351, 1016

Kurucz R.L., 1981, SAO Report 390

Kurucz R.L., 1988, In: McNally M. (ed.) Trans. IAU XXB, Kluwer, Dordrecht, p. 168

Muratorio G., Viotti R., Friedjung M., Baratta G.B., Rossi C., 1992, A&A 258, 423

Nahar N., 1995, A&A 293, 967 (the Iron Project)

Penston M.V., Benvenuti P., Cassatella A., et al., 1983, MNRAS 202, 833

Raassen A.J.J., Uylings P.H.M., 1998, J. Phys. B 31, 3137

Rossi C., Altamore A., Baratta G.B., Friedjung M., Viotti R., 1992, A&A 256, 133

Thorne A.P., Harris C.J., Wynne-Jones I., Learner R.C., Cox G., 1987, J. Phys. E 20, 54

Viotti R., Rossi C., Muratorio G., 1998, A&AS 128, 447