ANALYSIS OF VERY HIGH EXCITATION Fe I LINES ($4f$–$5g$) IN THE SOLAR INFRARED SPECTRUM

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Abstract. We present a detailed analysis of very high excitation lines ($4f$–$5g$) of Fe I which are present in the spectral region 2545–2585 cm^{-1} in high resolution spectra both in the laboratory and in the *ATMOS* solar spectra obtained from space. A value of the solar abundance of iron which agrees with the meteoritic value is derived.

Key words: infrared: stars – line: identification – Sun: abundances

1. Introduction

The identification of absorption lines in the near-IR solar spectrum as transitions between highly-excited Fe I levels (Litzén and Vergès, 1976; Johansson and Learner, 1990) has motivated further laboratory studies of even higher Fe I configurations for solar and stellar spectroscopy. The extraordinary quality of the solar IR spectrum obtained with the *ATMOS* space experiment (Farmer and Norton, 1989) offers the possibility to perform a fine analysis of hydrogenic lines of Fe I and to make a comparison between laboratory and solar spectra.

In the present paper we report on an analysis of the $3d^6 4s(^6\mathrm{D})4f - 3d^6 4s(^6\mathrm{D})5g$ supermultiplet based on laboratory FTS-spectra and on the *ATMOS* solar spectrum. The presence of $4f$–$5g$ lines in ground-based IR spectra of the sun and of α Tau (Ridgway *et al.*, 1984) was first reported by Johansson *et al.* (1991). However, the *ATMOS* spectra allow a much more accurate analysis of the $4f$–$5g$ lines than can be obtained from ground-based spectra. The identifications have been confirmed by calculated line strengths in comparison with observed laboratory and solar intensities. A full presentation of all data, and the detailed analysis, will be published elsewhere (Johansson *et al.*, 1992). The identifications we provide are confirmed in another paper in these proceedings by Schoenfeld *et al.* (1993).

2. Laboratory experiment and analysis

The laboratory spectrum used in our analysis of the $4f$–$5g$ supermultiplet has been recorded with the Fourier Transform Spectrometer (FTS) at Kitt Peak for

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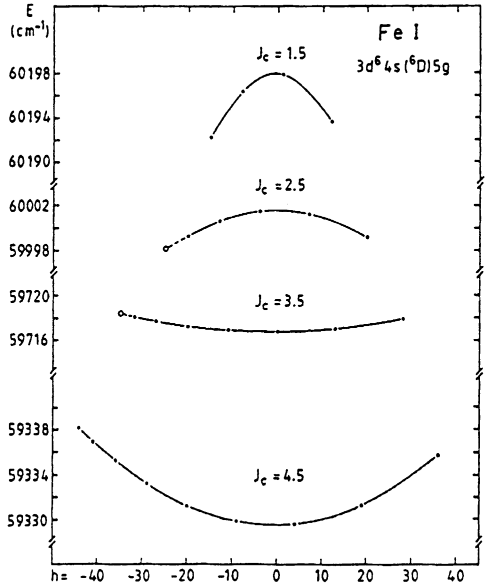

Fig. 1. The new $3d^6 4s(^6\mathrm{D})5g$ levels plotted as a function of $h = \mathbf{J}_{\mathbf{itc}} \cdot \mathbf{l}$, where $\mathbf{J}_c$ is the total angular momentum of the ^{6}D parent level and $\mathbf{l}$ is the orbital angular momentum of the outer $5g$-electron. The curves are drawn through the experimental points (dots) and predicted c.g. values for unknown level pairs (circles).

an extensive analysis of the Fe I spectrum (see, *e.g.*, Nave *et al.*, 1992). A hollow-cathode lamp of pure iron was run with neon at 3.7 torr and at a DC-current of 1.4 A. The wavenumber resolution is 11.9 mK. Similar FTS-spectra from Kitt Peak have earlier been used in the IR for solar identifications (Biémont *et al.*, 1985) and for laboratory and solar analyses (Johansson and Learner, 1990). However, it turns out that the spectrum used for the present work has a higher signal to noise ratio than earlier FTS-spectra, probably due to the water-cooling of the hollow-cathode. This has helped in the analysis of the $4f$–$5g$ transitions.

The analysis of the $3d^6 4s(^6\mathrm{D})5g$ subconfiguration has been performed in the same way as the $3d^6 4s(^6\mathrm{D})4f$ subconfiguration (Johansson and Learner, 1990), *i.e.*, by means of the application of the quadrupole approximation. These configurations are very well described by the JK-coupling scheme, meaning that the fine structure splitting of the parent term $3d^6 4s\ ^6\mathrm{D}$ in Fe II determines the gross structure. The electrostatic interaction between the outer $5g$ electron and the core separates level pairs built on the same parent level J_c. This separation is determined by the electrostatic parameter $\mathrm{F}^2(3d, 5g)$. By plotting the energy of the level pairs as a function of the scalar product $h = \mathbf{J}_c \cdot \mathbf{l}$, all level pairs associated with a particular parent level fall on a parabola (see Fig. 1), as the diagonal coefficients of $\mathrm{F}^2(d, g)$ are quadratic functions of h. The parabolas should be symmetric relative to $h = -1/2$. The change of the shape of the parabolas from "bowl-like" to "umbrella-like" was discussed by Johansson and Learner (1990). Probable deviations from a parabolic curve reveal either misidentifications or perturbations. In the case of $5g$, the deviations are smaller than 10 mK. Once the strongest transitions have been classified, the parabolas can be used to predict the rest of the levels. A few levels are still missing in the $5g$-subconfiguration due to missing levels in the $4f$-subconfiguration. We have indicated the position of the missing levels in $5g$ in Figure 1 with open circles.

We have also performed parametric calculations of the $3d^6 4s(^6\mathrm{D})5g$ subconfiguration by means of the Cowan code and calculated oscillator strengths. There is in general a very good agreement between laboratory intensities, calculated line strengths and oscillator strengths, derived from the solar spectrum by adopting an abundance of 7.51 for Fe in the usual logarithmic scale. Some small discrepancies still have to be investigated by a more thorough interpretation of possible level mixings or line blends.

A number of lines appearing in the 1350 cm^{-1} region in the *ATMOS* solar spectrum can certainly be identified by the next set of hydrogenic transitions in Fe I, *viz.* the $3d^6 4s(^6\mathrm{D})5g - 3d^6 4s(^6\mathrm{D})6h$ supermultiplet. There are no laboratory spectra of iron available in this wavelength region and the analysis has to be performed on the basis of the solar lines and the application of the quadrupole approximation.

3. Identifications in the Solar Spectrum

Between 2545 and 2585 cm^{-1}, more than 90% of the solar lines are due to $4f$–$5g$ Fe I transitions. All of these lines (about 100), which have excitation energies of 7.1 to 7.3 eV, have been identified without any doubt in the *ATMOS* solar infrared spectra. Figure 2 shows a comparison of laboratory and solar (observed and synthetic) spectra in the spectral region $\sigma = 2565$–2570 cm^{-1}.

4. Solar Analysis

These lines show typical shapes *i.e.*, they are broad with extended wings such as all other high excitation atomic lines. This is due to the expected increase of the damping constant with excitation energy. In Fe I, the profiles become nearly Lorentzian for excitation energies higher than about 6 eV.

Although relatively faint, these high excitation Fe I lines are very sensitive to the damping constants as shown in Figure 3 where we considered collisions with H atoms to be the main broadening mechanism. As it is well known that damping constants (γ_{coll}), calculated by means of Unsöld's approximation (1955), are too small (Blackwell *et al.*, 1984; Holweger *et al.*, 1991), the enhancement factor plays a crucial role.

The Stark broadening is expected to play a non-negligible role as the excitation energy increases (Chang and Schoenfeld, 1991; Carlsson *et al.*, 1992). In the absence of reliable data for our lines, we took it crudely into account using an approximate formula given by Cowley (1971) —see also Freudenstein and Cooper, (1978). Our results show that the Stark broadening is only about 1/3 of the Van der Waals broadening.

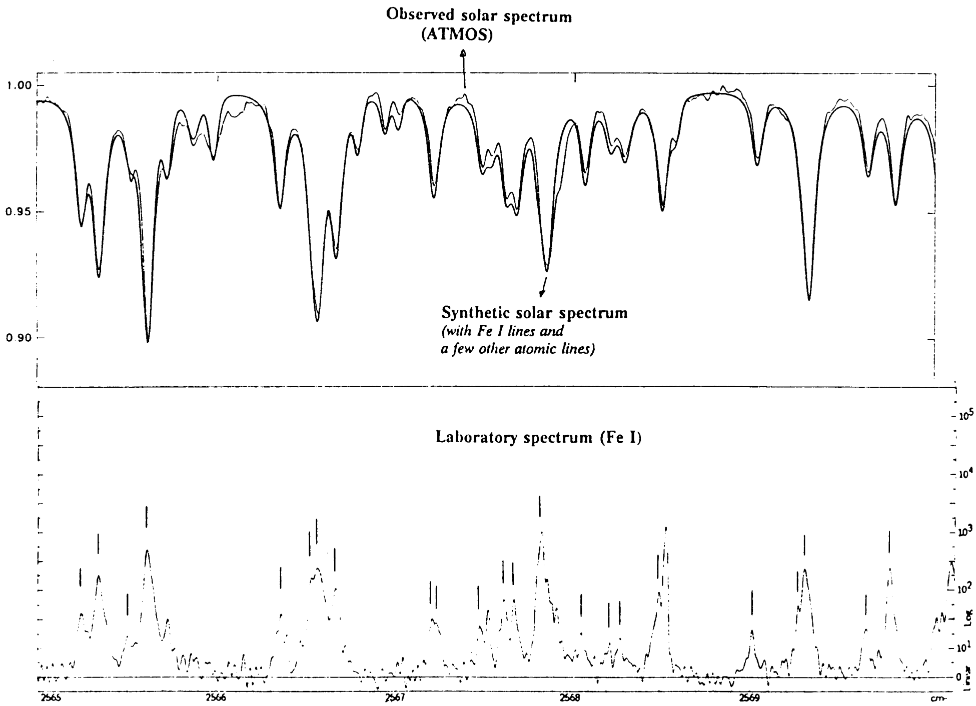

Fig. 2. Comparison of laboratory and (*ATMOS* and synthetic) solar spectra in the region 2565–2570 cm^{-1}.

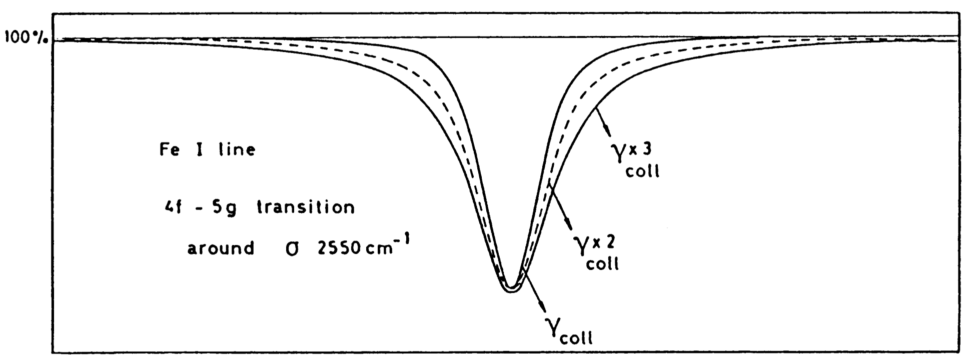

Fig. 3. Effect of an increase of the collisional damping constant (γ_{coll}) on the profiles of a typical $4f$–$5g$ iron line of about 5% central depth: there is a strong line broadening and the far wings become more and more important when increasing γ_{coll} by a factor 2 or 3.

We fitted synthetic line profiles to the observed solar spectrum for all our Fe I lines in the region $\sigma = 2545$–$2582\ \mathrm{cm}^{-1}$. Very good agreement is obtained, as can be seen in Figure 2 (which corresponds to $\sigma = 2565$–$2570\ \mathrm{cm}^{-1}$), for an enhancement factor of about 2 for the damping constant and for a solar abundance of iron, $A_{\mathrm{Fe}} = 7.51$, a value that is in perfect agreement with the meteoritic value (Anders and Grevesse, 1989).

5. Conclusions

These very high excitation lines of Fe I are much less sensitive than lower excitation lines to temperature uncertainties and to departures from LTE. Based on theoretical transition probabilities described in Section 2, they lead to a photospheric abundance of Fe, that agrees with values recently derived by Holweger *et al.* (1990) using lower excitation Fe I lines and by Holweger *et al.* (1991), Biémont *et al.* (1991), Hannaford *et al.* (1992) using Fe II lines: all of these results being in agreement with the meteoritic abundance of Fe.

We note that Fe I lines of still higher excitation energies ($5g$–$6h$) have very recently been identified in the *ATMOS* solar spectrum around $1350\ \mathrm{cm}^{-1}$ (Schoenfeld *et al.*, 1993).

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