Is LTE a Suitable Approximation for Fe I - based Diagnostics of the Thermal Structure of Sunspots?

N. G. Shchukina and J. Trujillo Bueno

_Instituto de Astrofísica de Canarias, E-38200, La Laguna, Tenerife, Spain_

**Abstract.** NLTE effects in iron lines are carefully investigated for the sunspot umbral model of Maltby _et al._ (1986). Our model atom is realistic: it has hundreds of levels including many high-excited ones among which infrared transitions take place. The self-consistent solution of the kinetic and radiative transfer equations is obtained using recently-developed multilevel transfer methods suitable for efficiently handling hundreds of radiative transitions in detail from the ultraviolet to the infrared. These NLTE multilevel transfer calculations allow us to investigate whether the currently-used LTE approximation is suitable for diagnosing the temperature structure of sunspots via Fe I lines.

1. **Introduction**

Although notable progress has been achieved in recent years concerning the physics of formation of iron lines in the _quiet_ Sun and in other cool stars (see the review by Rutten 1988, and his references to original work; see also Solanki & Steenbock 1988, Dravins & Nordlund 1990, Takeda 1991, Bruls 1991, Shchukina, Trujillo Bueno & Kostik, 1997) very little is known about the NLTE iron line formation problem in sunspots. Our present understanding stems mainly from one-dimensional (1D) multilevel transfer calculations using simplified atomic models, like that of Gigas (1986). This atomic model includes the lowest terms of Fe I, i.e. those with an excitation potential $\text{EPL} < 5 \text{eV}$, among which about 100 strong optical and ultraviolet (UV) radiative transitions take place. However, the real iron atom contains $\sim 300$ terms and 5000 multiplets which lead to a huge amount of diagnostically important UV, optical and _infrared_ lines. This atomic complexity and the fact that the solar atmospheric plasma is spatially inhomogeneous renders evident the need of detailed multidimensional radiative transfer (RT) simulations using realistic atmospheric and atomic models. The aim of this work is to go a step further towards this scientific objective using, for the moment, the 1D sunspot umbral model of Maltby _et al._ (1986), but carefully investigating possible NLTE effects considering a relatively complex iron atomic model that includes many UV, optical and infrared transitions.

---

1 On leave from the Main Astronomical Observatory, National Academy of Sciences, 252650, Kyiv-22, Ukraine

© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System
2. The Model Atom and the Solution Method

Starting from a revision of the atomic model of Gigas (1986) we have included many high-excited levels of Fe I close to the ionization threshold. We also added more terms in the lower part of the Grotrian diagram of Fe I taking into account their fine structure. Our model atom for Fe I - Fe II - Fe III now contains a substantially larger number of UV and optical lines and all the infrared (IR) lines that have equivalent widths larger than 100 mÅ in the observed solar photospheric spectrum. This improved atomic model will be described in full detail elsewhere. Here it suffices to mention that it includes about 250 levels and nearly 500 radiative bound-bound and bound-free transitions.

We obtained the self-consistent solution of the kinetic and RT equations using recently-developed iterative methods for multilevel transfer applications (Auer, Fabiani Bendicho and Trujillo Bueno, 1994; Trujillo Bueno and Fabiani Bendicho, 1995). We applied these fast methods of solution because they are suitable for 2D and 3D multilevel transfer modeling, which constitutes the next step of our ongoing research project on the iron line formation problem in cool stellar atmospheres.

3. NLTE Effects in Fe I Lines Formed in an Umbral Atmosphere

The following discussion is based on the total set of Fe I lines contained in our atomic model. In this paper we put particular emphasis on the following groups of lines currently used in solar polarimetry:

(A) Two lines of multiplet No. 1: \( \lambda 5247.052 \) and 5250.212 Å. These lines have a low excitation potential.

(B) Five lines of multiplets No. 553, 686, and 618: \( \lambda 5324.185 \), 5586.763, 5576.097, 6301.515, and 6302.507 Å. These lines have intermediate values of their excitation potential.

(C) Two infrared lines: \( \lambda 15648.50 \) and 15652.890 Å. These lines have a high excitation potential.

3.1. Departure coefficients

Fig. 1 shows the variation with height of the departure coefficients \( \beta_i = n_i/n_i^* \), where \( n_i \) and \( n_i^* \) are the NLTE and the LTE populations of level "i", respectively. It is worth noting the following points.

(i) In the umbral photosphere the populations of Fe I levels with an excitation potential \( EPL \leq 5.3 \) eV are close to LTE, while the Fe I levels of higher excitation potential are underpopulated.

(ii) In general, the larger the line excitation potential and the height in the umbral atmosphere the larger the deviations from LTE.

(iii) In the umbral photosphere the Fe II levels are slightly overpopulated.

(iv) In the umbral chromosphere there is an excess of neutral iron atoms and a deficiency of ions relative to LTE.

Multilevel NLTE transfer calculations using "quiet-Sun" photospheric models (Athay and Lites, 1972; Rutten, 1988; see also Shchukina, Trujillo Bueno and Kostik, 1997) show a sizable drop with height of the departure coefficients \( \beta \) of
the Fe I levels, which is due to the UV overionization coming from the hot radiation that exceeds the Planck function in the 3000-5000 Å wavelength region. At the low temperatures of the Maltby et. al. (1986) sunspot model the neutral stage of iron is the dominant one, just as at the higher quiet-Sun photospheric temperatures Fe II is the majority species. Therefore, for an umbral atmosphere the UV overionization mechanism can only produce relatively small population changes of the highly-populated Fe I levels.

3.2. Line Source Functions and Opacities

Deviations of the Fe I populations from the LTE values lead to changes in the line opacities and in the line source functions. The NLTE opacities can be estimated by scaling the LTE opacities by the value of the lower-level departure coefficient $\beta_L$. If the NLTE opacities differ from those found using LTE the heights in the atmosphere where $\tau_{\text{line}} = 1$ are different, i.e. one has optical depth shifts.

The fact that $\beta \sim 1$ in Fig. 1 for the Fe I lines having EPL $\leq 5.3$ eV shows that their optical depth shifts in the sunspot model of Maltby et. al. (1986) are small. The largest shifts occur for the Fe I lines with the highest excitation potentials. These lines are formed in deep umbral layers (below 200 km), and the optical depth shift for them does not exceed 20 km.

In order to quantify and visualize the deviations of the line source functions from the Planck function for the full set of Fe I lines of our atomic model we have done the following. For each Fe I line we calculated the excitation temperature $T_{\text{ex}}$ at the atmospheric height where $\tau_{\text{line}}(\text{NLTE}) = 1$, and also the electron temperature $T_e$ at the atmospheric height where $\tau_{\text{line}}(\text{LTE}) = 1$. The differences $(T_e - T_{\text{ex}})$ versus the height where $\tau_{\text{line}}(\text{LTE}) = 1$ are shown in Fig. 2 for the three types of Fe I lines mentioned above.

It is worth noting in Fig. 2 that the larger the atmospheric height where $\tau_{\text{line}}(\text{LTE}) = 1$ the larger the difference between the excitation and the electron temperature. Note also that the degree of deviation from LTE, i.e. how large $T_e - T_{\text{ex}}$ can be, depends on the excitation potential of the lower level of the line under consideration.

4. LTE versus NLTE Temperature Diagnostics

Is LTE a suitable approximation for Fe I - based diagnostics of the temperature structure of sunspots? From Fig. 2 we also conclude the following:

(1) Since $(T_e - T_{\text{ex}}) > 0$ the LTE approximation generally leads to a subestimation of the actual sunspot temperature.

(2) The assumption of LTE is suitable for lines of low EPL, like the 5247.052 and 5250.212 Å lines.

(3) With the exception of the 15648.50 and 15652.890 Å lines, the assumption of LTE may lead to significant errors for many other IR lines of high excitation potential.

(4) For lines of intermediate EPL the errors in the recovered temperature grow with the line strength. Such errors may be as large as 600 K for the strongest lines, like those with $\lambda$ 5324.185 or 5586.763 Å. For lines of moderate strength, like the 6301.515 and 6302.507 Å lines, the errors vary between 100 and 300 K.
Figure 1. The departure coefficients $\beta$ of the Fe I levels (dashed and dashed-dotted lines) and of Fe II (solid lines).

Figure 2. The differences between the electron temperature $T_e$ and the excitation temperature $T_{ex}$ versus the atmospheric height where $\eta_{\text{line}}(\text{LTE}) = 1$. Each of the indicated “big” black dots corresponds to lines used in solar polarimetry. The “small” black dots give the $(T_e - T_{ex})$-differences for individual lines of high excitation potential. The solid, dashed and dashed-dotted curves are polynomial fits corresponding to each of the groups of the full set of Fe I lines of our atomic model.
5. Conclusions

Using a realistic iron atomic model that also includes high-excited levels among which IR transitions take place, and applying efficient multilevel RT methods we have shown that NLTE effects in the sunspot umbral model of Maltby et al. (1986) mainly affects the line source functions of the Fe I lines, but not significantly the line opacities. The LTE approximation leads to errors in the recovered temperature that depend on the strength and on the value of the excitation potential of the particular Fe I line chosen for the diagnostics. LTE should be a good approximation for Fe I lines with an excitation potential smaller than about 2 eV, and also for the 15648.50 and 15652.890 Å IR lines. However, a subestimation between 100 and 600 K of the actual sunspot temperature may be obtained when assuming LTE for many other lines of intermediate and high excitation potentials. For the 6301.5 and 6302.5 Å lines currently used in solar polarimetry the LTE approximation may lead to errors that lie between 100 and 300 K.

The results shown in this contribution will be described in more detail in a forthcoming paper, where we plan to consider also other sunspot models like those presented by Severino et al. (1994).

Acknowledgments. Partial support by the Spanish DGES under project PB 95-0028 is gratefully acknowledged. Nataliya G. Shchukina would like to acknowledge the support of the Spanish Ministry of Education for a sabatical stay at the IAC. We also thank Dr. M. Vázquez for his support and interest in our work.

References