Non-Stationary Processes in Atmospheres of Early-Type Stars: Influence on Forbidden to Intercombination Ratio f/i

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We report the results of non-stationary level population modeling of highly ionized atoms in the atmospheres of early-type stars. We studied the influence of the fast heating and cooling processes on the ratio of forbidden to intercombination line intensities $R = f/i$ for He-like ions (CV, NVI, OVII, etc.) in X-ray spectra.

It is shown that the instantaneous ratio R_{m} for the non-stationary plasma varies by up to 4 orders of magnitude on short time scales (milliseconds) in comparison with the value for the stationary plasma. In the same time the value of R_{a} averaged on long time scales (hours and minutes) varies by up to 20%. Using the ratio R calculated in the case the stationary plasma for the non-stationary plasma can lead to an overestimation of the plasma electron density by up to 1–2 orders of magnitude.

1 Introduction

The density diagnostics of the X-ray emitted plasma of the early-type stars based on the forbidden-to-intercombination line ratio R showed that this ratio is much lower than that predicted for the homogeneous non-stationary plasma (e.g., [1]). This could be explained as follows:

- The stellar UV-radiation excites electrons in the upper level 1s2s $^3\mathrm{S}_1$ of the forbidden line f and populates the upper level 1s2p $^3\mathrm{P}_{1,2}$ of the intercombination line i, which weakens the line f and strengthens the line i.
- Bound electrons are excited from the upper level of the line f by free electrons, which decreases the line f. This happens if the X-ray radiation originates from the dense clouds in stellar atmospheres.

In this paper we outline an alternative hypothesis.

2 Processes in non-stationary plasma

We suppose that the level population in the stellar atmospheres can become non-stationary.

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Non-stationarity could be caused by collisions of the plasma flows in the region on the stellar magnetic equator or by nano-flares in the stellar atmosphere similarly to the solar ones.

The non-stationary level population can be described by the following equation:

$$\frac{dx_i}{dt} = n_e \sum_{j \neq i}^{N} x_j q_{ji} + \sum_{j=i+1}^{N} x_j A_{ji} - x_i \left(\sum_{j=1}^{i-1} A_{ij} + n_e \sum_{j \neq i}^{N} q_{ij} \right). \qquad (1)$$

Here x_i is the relative population of the i-th level, N is the number of levels considered, n_e is the electron density, q_{ji} is the excitation/deexcitation rate from the level j to the level i, A_{ij} is the corresponding Einstein A-value. In our models we used $N = 50$ levels, which was enough for a precise modeling.

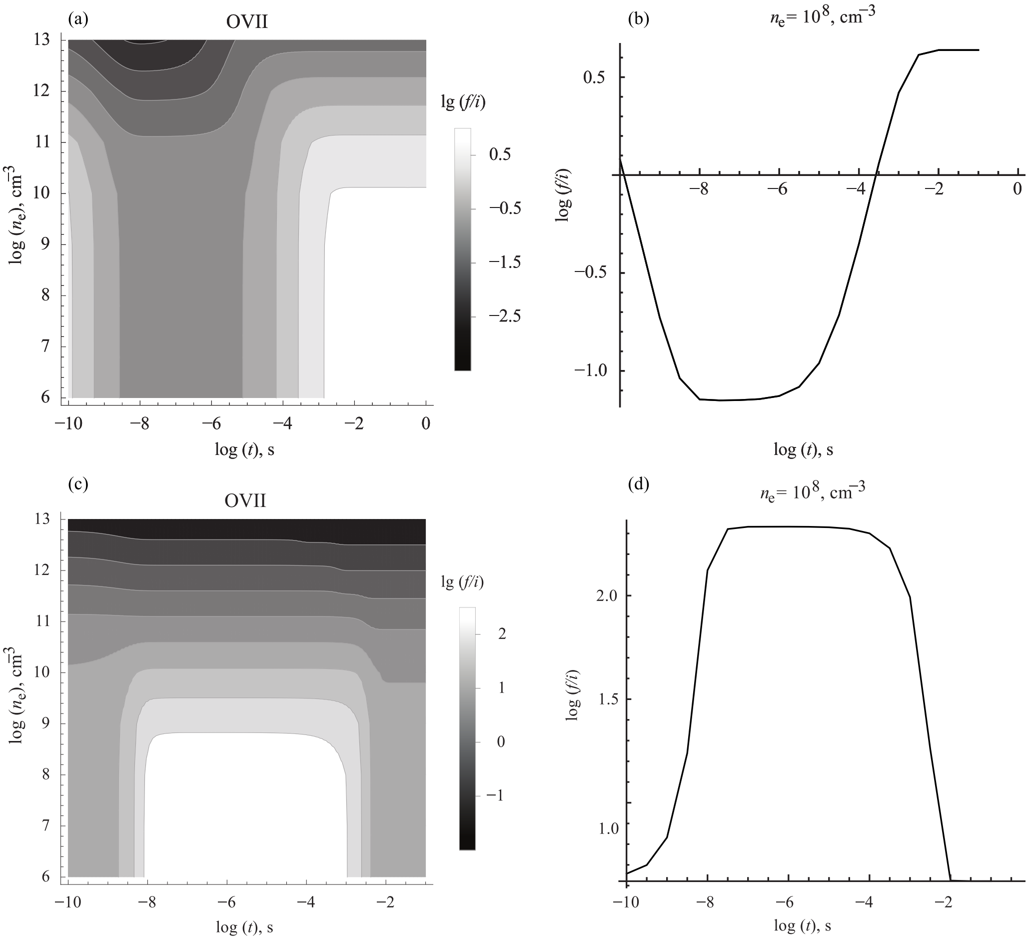

Figure 1: *Panel a*: Dependence of the ratio R_m on time and electron number density for OVII in the model for rapidly heated plasma. At $t = 0$, the plasma instantaneously heats from $T_\mathrm{e} = 10^6$ K to $T_\mathrm{e} = 10^7$ K, after the heating the temperature remains constant. *Panel b*: the same but for $n_\mathrm{e} = 10^8$ cm^{-3}. *Panels c, d*: the same as the upper row, but for rapid cooling from $T_\mathrm{e} = 10^7$ K to $T_\mathrm{e} = 10^6$ K.

Table 1: The parameters of the models: T_c is the plasma temperature in the "cool" state, t_c is the time of cooling, R_c is the stationary line ratio for T_c, the similar parameters for plasma heating are indexed with "h"

Model	T_c, K	t_c, s	T_h, K	t_h, s	R_c	R_h
A	5×10^5	3×10^{-2}	10^8	10^{-5}	9×10^{-3}	4×10^{-2}
B	5×10^5	10^{-5}	10^8	10^{-5}	3	2.75
C	5×10^5	3×10^{-2}	10^8	10^{-5}	9×10^{-4}	4×10^{-3}
D	5×10^5	10^{-3}	10^7	3×10^{-3}	7.5×10^{-1}	1.34
E	5×10^5	3×10^{-2}	10^8	10^{-5}	4.44	2.94
F	5×10^5	3×10^{-2}	10^8	10^{-5}	4.26	2.93
G	5×10^5	3×10^{-3}	10^7	2×10^{-3}	1.78	2.94
H	5×10^5	10^1	10^7	10^{-1}	5.61	8.25
I	5×10^5	10^{-3}	10^8	10^{-5}	2.98	2.75

Table 2: The results of the modeling, where n_e is the input model electron density, R_a is the averaged line ratio f/i, $\bar{n}_e$ is the electron density derived from R_a, when supposing the stationarity of the plasma

Model	Ion	n_e, cm^{-3}	R_a	$\bar{n}_e$, cm^{-3}	$\lg(n_e/\bar{n}_e)$
A	OVII	10^{13}	10^{-2}	8×10^{12}	0.1
B	OVII	10^{10}	–	–	–
C	OVII	10^{14}	2×10^{-3}	5×10^{13}	0.3
D	OVII	10^{11}	1.18	5×10^{10}	0.3
E	OVII	10^8	3.48	6×10^9	−1.8
F	OVII	10^9	3.35	6×10^9	−0.8
G	NVI	10^{10}	2.12	8×10^9	0.1
H	CV	10^9	6.24	8×10^8	0.1
I	OVII	10^{10}	2.93	–	–

3 Modeling and discussion

We used both a modified APEC [2] code and an additional code written in Mathematica to solve equation (1). We calculated the ratio R for various conditions of the plasma heating and cooling.

It can be seen that in the case of fast heating of low density plasma the ratio R decreases dramatically for a short time (see the "valley" in Fig. 1b). A similar behavior holds for the case of cooling: we can see the dramatic increase of the ratio R in the first second (the "plateau" in Fig. 1d). For stationary case, R holds in the interval 1–10.

Unfortunately, such fast processes could not be observed, since the exposure time of X-ray satellites is of the order of 10^4 s and above. That is why we studied the influence of non-stationary processes on the average f/i-ratio (R_a). The model parameters are presented in Table 1, results of the modeling are summarized in Table 2. It can be seen that the models E and F show significant difference between $R_{\rm a}$ and $R_{\rm c}$ and $R_{\rm h}$. It means that using the ratios R for the stationary plasma leads to the overestimation of the $n_{\rm e}$ derived from observations.

The parameters of heating and cooling which are given in the captions to Fig. 1 are typical of solar nano-flares or similar events in stellar atmospheres.

4 Conclusion

We showed that non-stationary processes could affect on the instantaneous forbidden-to-intercombination ratio $R_{\rm m}$ which increases (for fast cooling) or decreases (for fast heating) by up to 1–3 orders of magnitude during the first second. These processes could also strongly change the averaged ratio $R_{\rm a}$ by decreasing it by up to 20%. In this case one can incorrectly estimate the plasma electron density (errors can be of up to 2 orders of magnitude), when supposing the stationary level population in the plasma.

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