Time-dependent ionization in the envelope of supernovae of type II during the photosphere phase

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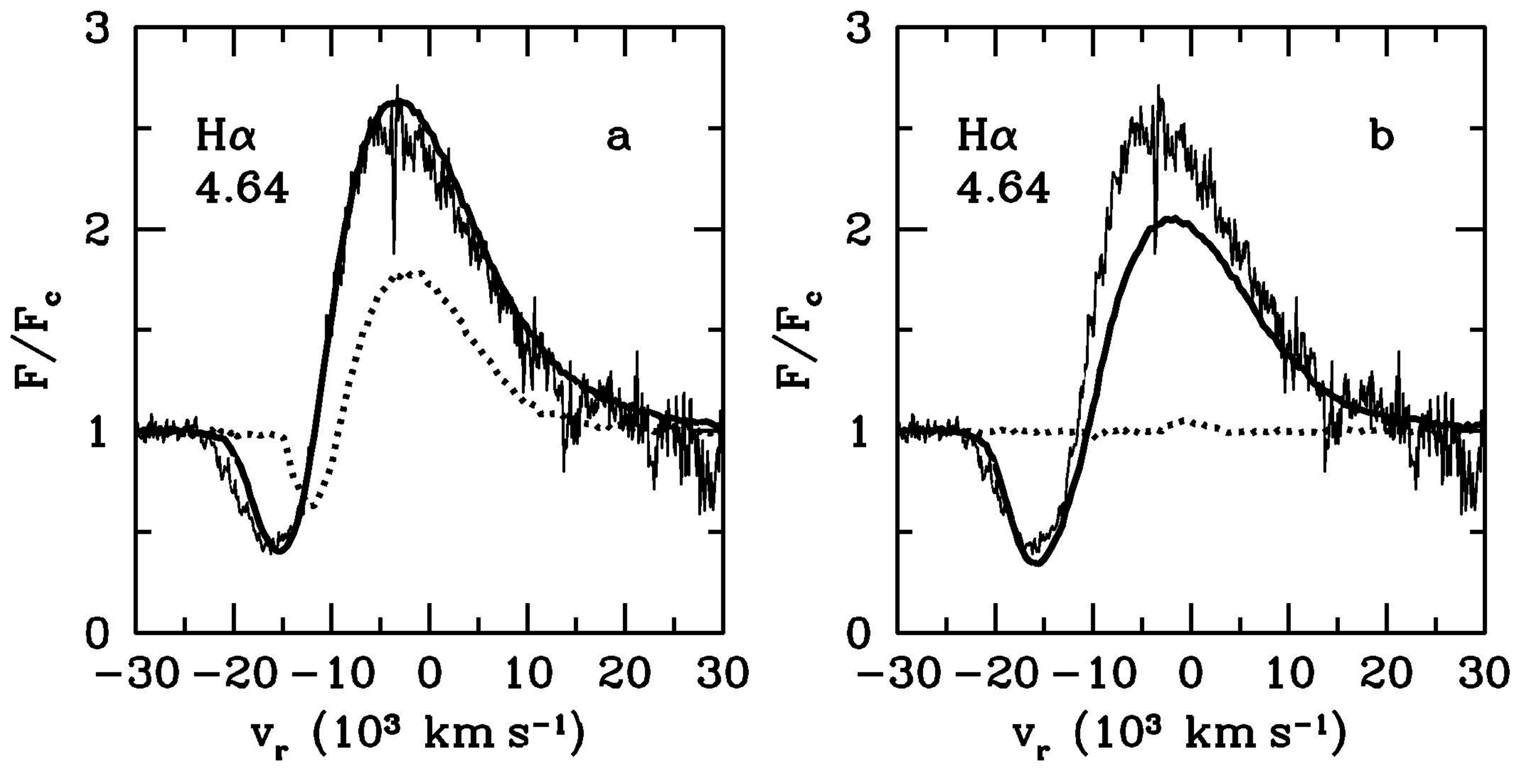
Introduction



The importance of allowance for the time-dependent effect in the kinetics at the photospheric phase during a supernova explosion has been confirmed by several independent research groups [1],[2],[3],[4]. The time-dependent effect provides a higher degree of hydrogen ionization in comparison with the steady-state solutions and strengthens the **Hα** line in the resulting simulated spectrum, with the intensity of the effect increasing with time. The time-dependent ionization allowed the spectra of peculiar **SN1987A** with a stronger **Hα** line to be obtained, which could not be done without mixing radioactive ^{56}Ni into the outer high-velocity layers in the steady-state approximation [3].

However, some researchers [5] argue that the time-dependent ionization effect is *unimportant*. Its allowance leads to an insignificant strengthening of **Hα** in their modeling only in the *first days* after the explosion. They illustrate this based on their computations with the **PHOENIX** software package with the models of **SN1987A** and **SN1999em** as an example. An important factor affecting the intensity of the time-dependent effect in their calculations is the number of levels in the model of the hydrogen atom.

Thus, the conclusion of the various research groups disagree. Within our formulation of the problem, we will attempt to answer the question of whether the time-dependent ionization effect is important or not and if it is important, then what can affect its intensity. We will demonstrate the importance of the time-dependent effect with the models of **SN1999em** as an example using the new original **LEVELS** software package [17].

Modeling

Our approach is to split the problem into two stages. Initially, we take the profiles of density, envelope expansion velocity, matter temperature, radiation color temperature, and the photospheric radius from our modeling with the **STELLA** code [6]. Initially, the presupernova is modeled. In the next step, the opacity table is computed by taking into account the absorption in spectral lines in a medium with a velocity gradient (*the expansion opacity*). Finally, the time-dependent radiative transfer equation is solved for each frequency group in the two-moment approximation in each Lagrangian zone simultaneously with the hydrodynamic equations. The equation of state treats the ionization in Saha's equilibrium approximation. The code also takes into account the scattering of photons by electrons.

At the next step, the hydrodynamic and thermodynamic parameters of the supernova obtained with **STELLA** are subsequently used as input into **LEVELS** for a self-consistent solution of the complete time-dependent (or steady-state) kinetic system of level population equations with the radiative transfer equations in Sobolev's approximation when the LTE approximation is already abandoned. In this step, the chemical composition of the expanding envelope can be specified. We consider the R450_M15_Ni004_E7 model of **SN1999em** from [7] with a presupernova radius R = 450 R⊙, mass M =15 M⊙, and an explosion energy of 7×10^{50} erg at a distance D ~ 7.5 Mpc to the galaxy NGC 1637, where the supernova exploded.

For strong resonance lines we take into account continuum destruction probability inside Sobolev resonance regions - the so-called *"U-function"* approximation [13]. For the ultraviolet and optical bands, $\nu < \nu_{LyC}$, we use the approximation of an optically thin medium. For the hard frequency range ($\nu \geq \nu_{LyC}$), we assume a thermodynamic equilibrium between radiation and matter. We consider models with a pure hydrogen shell and models with metal admixtures. The atomic data for hydrogen were taken from the flexible atomic code (**FAC**) [8] computations for a model atom with a fine structure. The atomic data for iron were taken from **IRON** project through the **Wm-Basic** interface [9]. Proton impacts are taken into account in models where hydrogen is interpreted with a fine structure [10]. The **FAC** data were "folded" into the so-called "*superlevels*" [11] for model with the *l*-equilibrium in the hydrogen, implying that at a fixed principal quantum number the populations of the fine-structure sublevels are proportional to their statistical weights. The calculations take into account the direct radiative interaction of the fine structure components, which is effective due to Doppler shift of the photon frequencies in the expanding shell [12].

Results

There are three different cases under consideration:

1) Pure hydrogen envelope with *l*-equilibrium approximation.
2) Pure hydrogen envelope with fine-structure.
3) Hydrogen envelope with *l*-equilibrium approximation with iron admixtures.

For **case 1** our calculations show that the populations of levels with n ≥ 3 are much smaller than that of the first excited level. Accordingly, the total effective population rate of the ground level due to the escape of resonant photons from the profile for these levels is much lower (by two or three orders of magnitude for deep near-photospheric layers) than the escape rate of **Lα** photons. An increase in the number of levels in the model atom (from 10 up to 30) affects very weakly this total rate. And **Hα** p-cygni profiles changes very weakly with the increasing of the number of levels for different days after explosion. Thus, in our case, we **do not confirm** the conclusions from [5] about the removal of the time-dependent effect as the number of levels increases.

Remarkably, the most important collisional processes in this case are bound-bound processes between first and second levels.

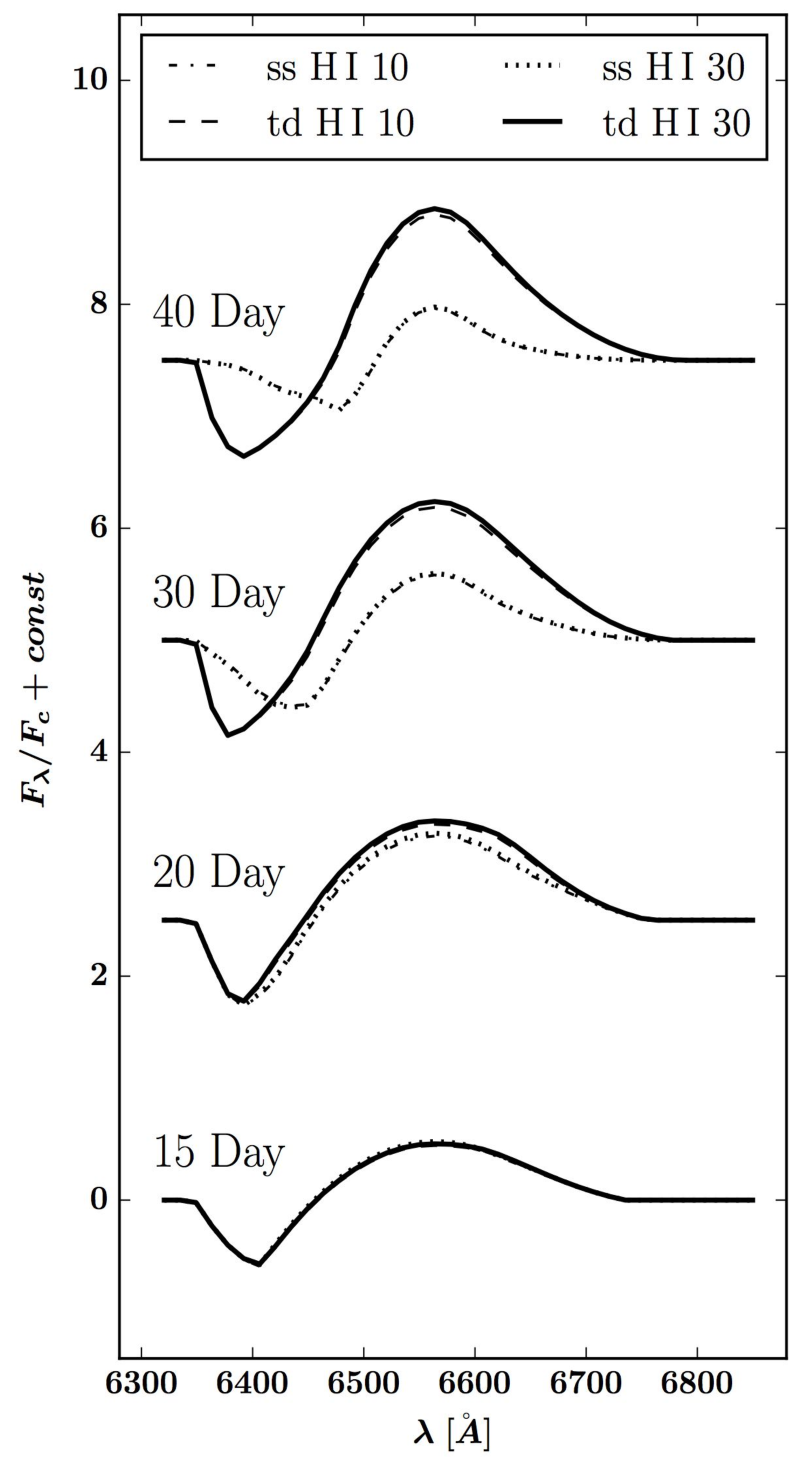
Taking into account the fine structure in the hydrogen atom in **case 2** leads to a weakening of emission in **Hα** p-cygni profiles both in the case of steady-state and in time-dependent, but does not cancel the time-dependent effect.

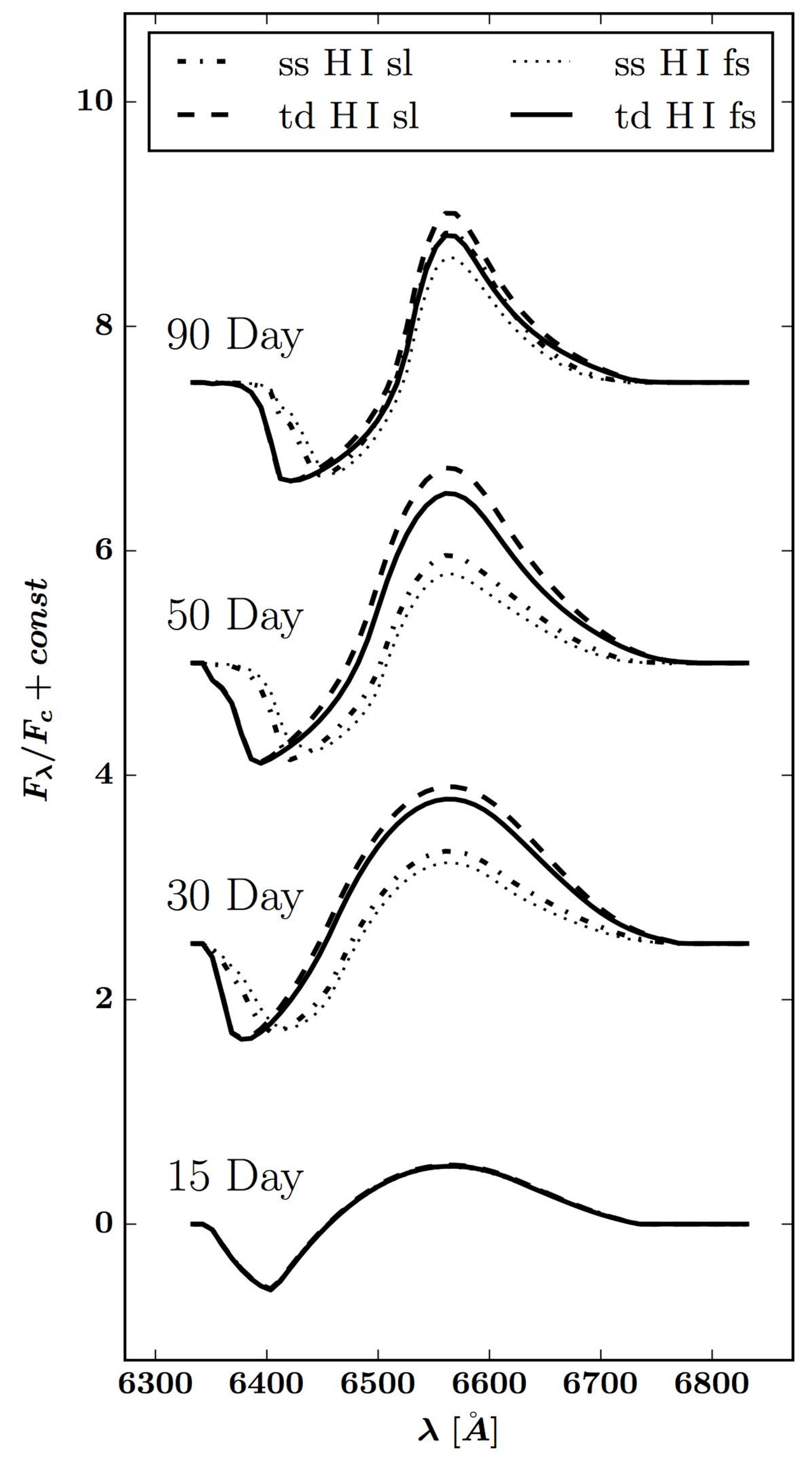
Since the first level of hydrogen in our formulation of the problem is in detailed balance with the continuum, the following channels are dominant and determine the population of the first level: the two-photon decay, the escape of **Lα** photons, and, to a lesser degree, the collisional imbalance of the second level of hydrogen. This leads us to conclude that to weaken the time-dependent effect, the rates of the processes between levels 2 and 1 of the hydrogen atom need to be "accelerated". This implies an increase in the number of included channels between these levels. Such an increase can be achieved if we abandon the purely hydrogen chemical composition and take into account the contribution of additional "absorbers". There are two additional channels for an optically thick (in the **Lα** line) SN envelope: the absorption of photons in flight in continuum [13],[14] and the absorption in metal lines (a large number of **Fe II** and **Cr II** lines are in the vicinity of **Lα**) followed by cascade fragmentation to softer photons [15]. Thus we come to the **case 3**.

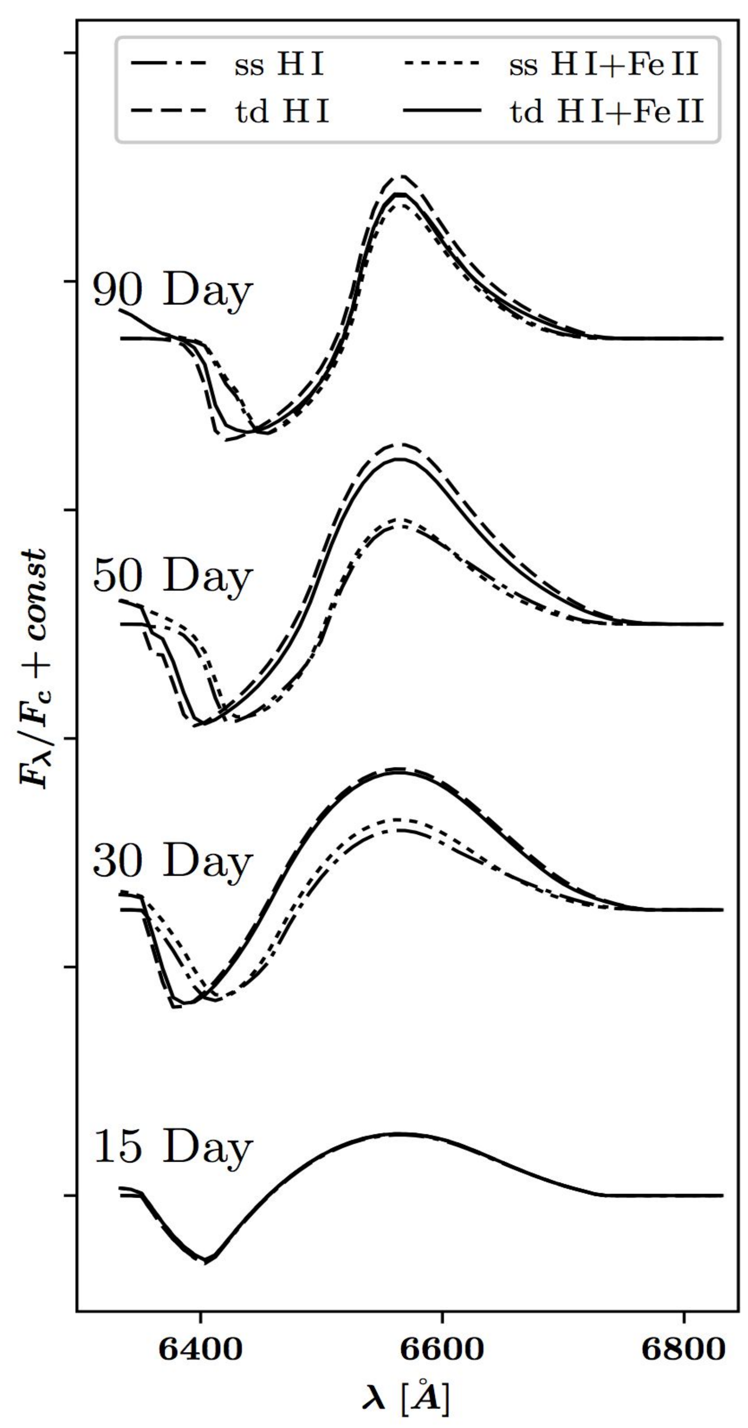
In order to calculate the probabilities for the loss of a photon in flight (the first channel) we apply for all resonance Lyman lines the approximation of [14]. For all other strong lines we apply "*U-function*" approximation. We will assume for the second channel that the metals are represented by **Fe II** ions and consider only the transitions from the lower **a^{4}D** term with an excitation energy of **~1eV**. We will assume that all **Fe II** lines are very close to the center of the Voigt **Lα** line profile. The list of lines was taken from [16].

The self-consistent solution for **case 3** shows that emission in **Hα** profiles in the steady-state increases while emission in time-dependent decreases. So the time-dependent effect is weakened but does not disappear completely. Consequently, the abundance of iron (and other metals capable of absorbing **Lα**) in the SN envelope is an important factor affecting the intensity of the time-dependent effect.

We have confirmed that **time-dependent effect** in the envelope of SN II during photosphere phase **is important**.







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