Freeze-out Effects in Hydrogen and Helium Lines of SN 1987A at the Early Photospheric Epoch

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Abstract. We have developed a time-dependent model of ionization, excitation and energy balance of SN 1987A atmosphere at the photospheric epoch to study early behavior of hydrogen and helium lines. The ionization freeze-out effects play a key role in producing both the strong H$\alpha$ during nearly the first month and the He I 5876 Å scattering line on day 1.76. Using an extended reaction network between hydrogen molecules and their ions demonstrates that ion-molecular processes are likely responsible for the blue peak in H$\alpha$ profile at the Bochum event epoch.

1 Introduction

We understand a spectrum formation of SNe II not better than we do the hydrogen and helium spectra of SN 1987A at the early photospheric epoch. Despite many attempts to explain H$\alpha$ and He I 5876 Å lines we are still far from satisfactory results [1,2,3,4]. The stumbling block is that any model produces too week H$\alpha$ and He I 5876 Å at the early photospheric epoch.

Yet, it has already become clear that a residual ionization (freeze-out effects) may result in the enhanced excitation of hydrogen compared to steady-state regime [5]. However, in our previous study [6] we assumed simple laws for the behavior of electron temperature in the atmosphere. Here we will confirm a vital role of freeze-out effects in the hydrogen excitation at the photospheric epoch using the upgraded model in which time-dependent chemical kinetics is solved along with time-dependent energy balance. Moreover, here we consider neutral helium, not only hydrogen, and will show a key role of the time-dependent kinetics for He I 5876 Å line too.

We also recapitulate here our previous results on modeling the blue peak of H$\alpha$ at the Bochum event phase upon the basis of the time-dependent kinetics with hydrogen-composed species [6]. This will demonstrate that not only first-order effects, like freeze-out, but subtle molecular processes may be also important for hydrogen spectrum formation in SN II.

2 Model and Input Physics

The atmosphere model is based on the hydrodynamic model [7] with a 15$M_\odot$ ejecta and a kinetic energy of 1.9$\times$10$^{51}$ erg. The radiation field is treated in the
Fig. 1. Time evolution of Hα from day 1.76 to 29.68 (a-d) and He I 5876 Å on day 1.76 (a) in SN 1987A. The observed spectra from day 1.76 to 8.69 \[12\] and on day 29.68 \[13\] (thick solid line) are compared to those computed with the full time-dependent energy balance (thin solid line), with adiabatic evolution of the kinetic temperature (short dashed line), with the electron temperature equal to the local radiative temperature (long dashed line), and for the steady state (dotted line)

approximation of sharp photosphere. For t<1.8 days the radiation field in continuum is described by the photospheric radius and effective temperature, taken from the hydrodynamic model, and at later epoch by the empirical values \[8\] and by the UV and optical observations \[9\]. The line radiation transfer is treated in the Sobolev approximation \[10,11\]. Electron temperature in the atmosphere is determined from solving the time-dependent energy equation.

The following elements and molecules are calculated in non-LTE chemical kinetics: H, He, C, N, O, Ne, Na, Mg, Si, S, Ar, Ca, Fe, H⁻, H₂, H₂⁺, and H₃⁺. All elements but H are treated with the three ionization stages. The level populations of H and He I are calculated for 15 and 29 levels, respectively, while other atoms and ions are assumed to consist of the ground state and continuum. The
Fig. 2. *Left panel*: The role of molecular reactions for the Bochum event. (a) Hα profiles on day 29.68 calculated in time-dependent approach with (*thin solid line*) and without (*dotted line*) molecular reactions. (b) The behavior of the Sobolev optical depth of Hα in both models. *Right panel*: Physical conditions in the supernova atmosphere (v > 10700 km/s) on day 4.64. (c) The density (*thick solid line*) and electron temperature (in units of 1000 K). The temperature is given for the model with the full energy balance (*thin solid line*) and for that with the adiabatic approximation (*dotted line*). (d) The behavior of the Sobolev optical depth for Hα and fractional abundance of H⁺ for both models.

reaction network involves all bound-bound and bound-free, radiative and collisional processes for atoms and ions, and 7 radiative and 37 collisional processes for molecules.

3 Results and Discussion

We have developed the time-dependent chemistry model coupled with the time-dependent energy balance at photospheric phase and investigated spectra of SN
1987A. The fit between the observed and calculated Hα profiles on days 1.76, 4.64, 8.69, and 29.68 and those of He I 5876 Å line on day 1.76 is fairly good in Fig. 1 indicating that our model reflects the reality reasonably well. However, we admit that on day 1.76 our assumption on the sharp photosphere may be responsible for the deficit of the calculated Hα and He I 5876 Å net radiation.

The time-dependent effects in the Hα and He I 5876 Å lines are remarkable in producing the strong absorption both in Hα and He I 5876 Å lines on day 1.76 (Fig. 1a). Moreover, a relative contribution of time-dependent effects to Hα increases in time (Fig. 1). No doubts, the ionization freeze-out plays a key role in producing the ionization and excitation of hydrogen during at least first month. At later epoch the non-thermal ionization and excitation from radioactive 56Ni decays become important.

After about day 20 molecular processes neutralizing ionized hydrogen (mainly H− + H+ → 2H) dominate over recombination close to the photosphere. This results in the non-monotonic radial dependence of the Hα Sobolev optical depth that is blamed for the blue peak in Hα at Bochum event phase (Figs. 2a,b). Earlier we have used the adiabatic approximation for electron temperature. While it is a good approximation for the outer layers, we demonstrate that the full time-dependent energy balance should be solved to produce more confident results in the time-dependent models (Figs. 2c,d).

4 Conclusions

Our present study of the time-dependent effects and the influence of molecules and radioactivity in the photospheric epoch of SN 1987A may be summarized as follows:

• the time-dependent effects are a key prerequisite for the strong Hα line during nearly the first month and the He I 5876 Å line on day 1.76;
• the additional excitation from radioactive 56Ni decays is not required to account for the Hα line during about the first month;
• the molecular processes among hydrogen-composed species turn out important factor of hydrogen neutralization which is manifested by the emergence of the blue peak of Hα at the Bochum event phase.

We believe that these effects are important for normal SNe II-P at the plateau epoch as well.

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