Profiles for density and temperature dependence of the far red wing of the Lyman $\alpha$ line compared

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Abstract. A reliable determination of the line profiles of atomic hydrogen for physical conditions of cool white dwarfs requires a unified theory which takes into account both the singlet and triplet transitions contributing to Lyman alpha using accurate interaction potentials and radiative dipole transition moments. We show that multiple perturber effects have to be considered using the autocorrelation formalism. A comparison with experimental laboratory spectra of cool dense plamas also shows that indeed multiple H-perturbers are an important influence in the far wing extending to 3000 Å in the ultraviolet. Under cool dense white dwarf atmosphere conditions, multiple perturber collisions for the singlet states contribute more to the ultraviolet opacity than binary collisions of the triplet states.

1. Introduction

An accurate determination of the line broadening of the Lyman series of atomic hydrogen has been shown to be fundamental in the interpretation of UV and FUV spectra of DA white dwarfs. The pseudocontinuum due to the $b \, ^3\Sigma_u^+ \rightarrow a \, ^3\Sigma_g^+$ triplet transition which contributes to the red wing of the Lyman $\alpha$ line perturbed by neutral hydrogen was recently investigated by Kowalski (2006) and Kowalski & Saumon (2006) to improve previous calculations of atmosphere models of white dwarfs.

We will show that at the low temperature of cool white dwarfs the contribution of the singlet $X \, ^1\Sigma_g^+ \rightarrow B \, ^1\Sigma_u^+$ transition cannot be neglected in the calculation of Lyman $\alpha$ profile perturbed by neutral hydrogen. A comparison with experimental spectra also shows that indeed multiple H-perturbers contribute to the broadening that makes the far wing. The collisional effects must be treated by using the autocorrelation formalism described in Allard et al (1999).

2. Line profiles for $T=10000$K, variation with density of neutral hydrogen

Many of the problems in collision induced radiative transitions have been solved within the one-perturber approximation. At very low densities, the binary model for an optically active atom in collision with one perturber is valid for the whole profile except the central part of the line.

Figure 1 shows the prominent satellite due to interacting neutral hydrogen atoms in the $X \, ^1\Sigma_g^+$ ground electronic state making free-free transitions to the $B \, ^1\Sigma_u^+$ excited state.

In this work we use the most recent molecular data of Spielfiedel 2003, Spielfiedel et al 2004.
The contribution of the $X \rightarrow B$ transition is identical to the first order of the expansion shown in Fig. 1.

For this low density ($n_H = 10^{17}$ atoms cm$^{-3}$) the one-perturber approximation is valid, and the total profile above 1800 Å is due to the triplet $b \rightarrow a$ transition.

The semi-classical methods also can be extended by unified theories of line broadening to permit an inclusion of the effects of multiple collisions (Allard 1982). Figure 2 shows the total profile which takes into account the 4 allowed transitions, the $X \rightarrow B$ and $X \rightarrow C$ singlet transitions, and the $b \rightarrow a$ and $b \rightarrow i$ triplet transitions.

The red wing is dominated by the contribution of multiple-perturber collisions and the expansion of the autocorrelation function in density (Royer 1971, 1978) has to be made to the fourth order to be comparable with the result obtained from a unified calculation.

When the density is as high as $n_H = 10^{21}$ atoms cm$^{-3}$, the one-perturber binary approximation is no longer valid.

The total profiles shown in the figures are the Fourier transforms of the correlation function given by Eq. 121 of Allard (1999), in which the contributions from different components of the transition enter with their statistical weights. The figures also show the individual components for comparison, weighted as if they were the only contribution to the profile.

3. Variation with temperature
The appearance of an extended wing shown in Fig. 3 is sensitive to temperature because of the variation of the modulated transition dipole moment with temperature. Figure 4 illustrates that there is no contribution from triplets above 1900 Å (-30000 cm$^{-1}$) for $T=5000$ K because the modulated transition dipole moment is too weak.

Figure 5 shows that for 5000 K the $X \rightarrow B$ and $b \rightarrow a$ quasi-molecular transitions both contribute and have to be included.

Because of the weighting, the singlet $X \rightarrow B$ makes only 1/3 of the total line far wing strength. Nevertheless, its contribution through multiple perturber collisions dominates the 1800 to 3000 Å region.

Consequently, the ultraviolet triplet $b \rightarrow a$ transition does not, by itself, account for the far red wing of Lyman α profile broadened by collisions with atomic hydrogen. Kowalski & Saumon (2006) in their analysis of the missing opacity in cool dense white dwarf stars considered the triplet contribution but did not include multiple perturber effects.
4. Laboratory spectra
Satellites in the far wings of Lyman α are seen in the emission spectra of plasmas produced when a pulsed laser excites an H₂ gas target (Kielkopf & Allard, 1998). The laser-produced plasma sources in atmospheric density H₂ were shown to generate profiles of Lyman α that extend in the wing up to above 1600 Å. Those experiments cover conditions over which only binary collisions were important in the spectral regions shown.

Kielkopf & Allard (2000) described experiments at higher density extending farther into the Lyman α wing where the effects of more than one perturber acting simultaneously on the radiating atom appear.

The spectrum of Lyman α from a dense atomic hydrogen plasma exhibits a far wing that can be followed to 3000 Å as shown in Fig. 6. A shoulder in the wing above 2500 Å is evidence of multiple neutral H perturbers acting simultaneously on an excited 2p H atom.

5. Synthetic spectra of cool white dwarfs
Previous Lyman α line profile calculations were done at low temperatures and were included in atmosphere models by Wolff et al. (2002), and by Kowalski & Saumon (2006). Both papers presented a comparison of synthetic spectra to observed spectra of BPM4729. Unfortunately, neither paper shows the actual line profiles that were used. In Fig.3 of Wolff et al. (2002), the change of slope of the synthetic spectrum may be due to the second satellite. Since the transitions and the corresponding potentials which were used were not specified in Wolff et al. (2002), we cannot know if the b → a transition was included. Their predicted profile in a pure hydrogen atmosphere does not agree with the observation. Kowalski & Saumon (2006) were successful in reproducing the spectrum of BPM4729 from the ultraviolet to near IR. They used a line profile calculated in the quasi-static approximation for only the b → a transition in H-H collisions, and they also included collisions with H₂, but the transitions and symmetries for the corresponding H₃ potentials which have been taken into account in this work are not specified in their paper. We have seen in our work reported here and in Allard and Kielkopf (2009) that the b → a transition alone is inadequate to account for the spectrum above 1600 Å at elevated temperatures.
atomic hydrogen densities. Moreover, we used the H₃ potentials shown in Figure 1 of their paper to compute far wing spectra using the autocorrelation formalism. Fig. 7 shows that the red wing that would be produced by these potentials does not extend beyond 3000 Å.

References
Allard N F & Kielkopf J F 1982 Rev. Mod. Phys. 54 1103
Allard N F & Kielkopf J F 2009 A&A 493 1155
Allard N F Royer A Kielkopf J F & Feautrier N 1999 Phys. Rev. A 60 1021
Kielkopf J F & Allard N F 1998 Phys. Rev. A 58 4416
Kielkopf J F & Allard N F 2000 Connecticut meeting of the APS, Division of Atomic, Molecular, and Optical Physics June 14-17
Kowalski P M 2006 ApJ 651 1120
Kowalski P M & Saumon D 2006 ApJ 651 L137
Royer A 1971 Phys. Rev. A 3 2044
Royer A 1978 Acta Phys. Pol. A 54 805
Spielfiedel A 2003 J. Mol. Spectrosc. 217 162
Spielfiedel A Palmieri P & Mitrushenkov A O 2004 Molec. Phys. 102 No. 21 2249
Wolff B Koester D & Liebert J 2002 A&A 385 995