Publ. Astron. Obs. Belgrade No. 100 (2021), 401 - 404 *Poster*

RYDBERG ATOMIC COMPLEXES IN ASTROPHYSICAL PLASMAS

V. A. SREĆKOVIĆ[1], LJ. M. IGNJATOVIĆ[1], M. S. DIMITRIJEVIĆ[2] and V. VUJČIĆ[2]
[1]*Institute of Physics Belgrade, UB, PO Box 57, 11000 Belgrade, Serbia*
[2]*Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia*

Abstract. In this contribution, we further investigate processes which include Rydberg atomic complexes important for the different astrophysical environments. The range of the used physical parameters covers the area important for plasma modeling from astrophysical standpoint (white dwarfs, central stars of planetary nebulae, etc). Naturally, these results can be of interest and use in investigation of different laboratory plasmas. Also, we present overview of future developments and needs in the areas of Rydberg collisional processes.

1. INTRODUCTION

Elementary processes which involve highly excited i.e. Rydberg atoms (RA) with principal quantum number $n \gg 1$ in different environments still attract attention of scientists as they may be connected with the characteristics of many types of laboratory and astrophysical plasmas (see e.g., Gnedin et al. 2009; Mihajlov et al. 2016, Marinković et al. 2017; Dimitrijević et al. 2020). Recently in the laboratory Rydberg atoms with n close to 10^2 are being explored (especially experiments with so-called Rydberg-atom matter (RM), i.e., clusters of Rydberg atoms), whilst the astrophysicists now observe the RA with n close to 10^3 and RM in space connected with low-density condensed dark matter (Badiei & Holmlid 2002).

The aim of this paper is consideration of atom-Rydberg atom $(A + RA)$ collision processes which simultaneously occur i.e. collisional ionization/ recombination processes and excitation-deexcitation processes. In this contribution we studied two types of collisional ionisation/recombination processes: the non-symmetric processes

$$A^*(n) + X \Leftrightarrow e + \begin{cases} AX^+, & \text{(1a)} \\ A + X^+, & \text{(1b)} \end{cases}$$

and the symmetric-processes

$$A^*(n) + A \Leftrightarrow e + \begin{cases} A_2^+, & \text{(2a)} \\ A + A^+, & \text{(2b)} \end{cases}$$

where A, X, A^+ and X^+ are atoms and their atomic ions in the ground states, $A^*(n)$ is the atom in a highly excited (Rydberg) state, A_2^+ and AX^+ are the molecular ions in ground electronic states. The investigated excitation-deexcitation processes are

$$A^*(n, l) + A \Leftrightarrow A + A^*(n', l). \quad (3)$$

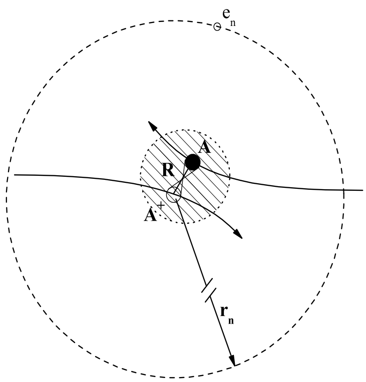

Figure 1: Schematic presentation of RA+A collision (the region of R where the outer electron is collectivized is shaded; Gnedin et al. 2009).

The theory and mechanism of the processes Eqs. (1)-(3) as well as the respective numerous literature have been recently presented in details in Mihajlov et al. (2012) and Srećković et al. (2020). Here we will describe shortly its main features.

2. THEORY

Here will be analyzed the current state of the research of ionisation/ recombination processes and excitation and de-excitation processes in $A + RA$ collisional reaction. Since these processes are treated already for some time on the bases of the so-called dipole resonant mechanism (DRM), we will describe shortly its main features. In this description of the collisional ionisation and excitation events, it is envisaged that processes are induced by the dipole part of the electrostatic interaction between the outer Rydberg electron and the inner ion-atom system. Here R is the internuclear distance in the considered collision system, and $r_n \sim n^2$ the mean radius of e.g. atom $A^*(n)$. The resonant mechanism works in that part of the region $R \ll r_n$, where the ion-atom sub-system $A^+ + A$ of the system $A^*(n) + A$ can be treated as a quasi-molecular complex. Fig. 1 illustrates the mentioned DRM as a resonant energy exchange within the electronic component of the collision system $A^*(n, l) + A$: the transition of the subsystem $A + A^+$, from excited electronic state with the energy $U_2(R)$ in the ground electronic state with the energy $U_1(R)$ is followed by the simultaneous transition of the Rydberg electron from the initial bound state.

3. ASTROPHYSICAL PLASMAS

The solar atmosphere modeling: The influence of collision processes with Rydberg atoms (1)-(3), on hydrogen atom excited-state populations in solar photosphere has been examined. It has been concluded that the considered collision processes dominate over the relevant concurrent electron-atom and electron-ion processes in almost whole solar photosphere (Mihajlov et al. 2016; Srećković et al. 2020). It is shown that these processes are important for the non-local thermodynamic equilibrium modeling. In

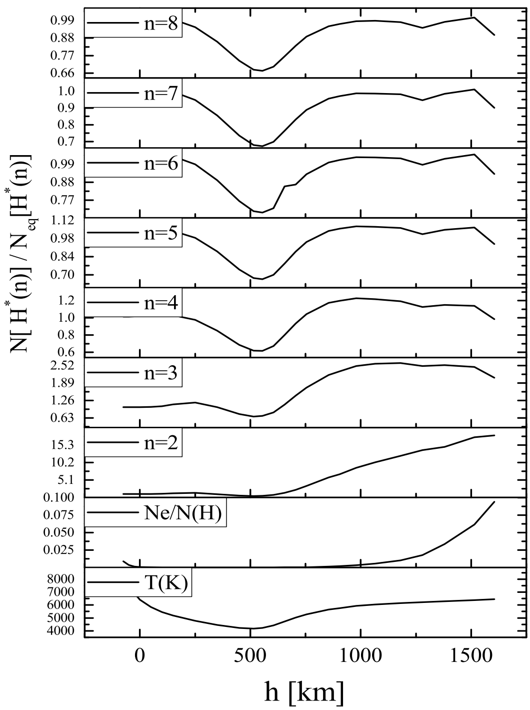

Figure 2: The ratio $N(\mathrm{H}^{*})(n)/N(\mathrm{H}^{*}_{eq})(n)$, as a function of height h. The eq stand for excited atom densities corresponding to thermodynamical equilibrium conditions for given T.

Fig. 2, deviations of non-LTE populations of excited hydrogen atom states with 2 $\leq n \leq$ 8, in solar photosphere are illustrated.

The atmospheres of late type (M) stars: The examined processes (1)-(3) with RA and Rydberg complexes influence to the populations of all hydrogen atom excited states. This suggest that these processes, due to their influence on the excited state populations and the free electron density, also should influence on the atomic spectral line shapes in late type (M) stars. The line profiles are synthesized with PHOENIX code, and line shape analysed with and without inclusion of processes (1) and (2).

AGN BLR clouds: The possibility that the $A + RA$ collisions, may be useful for the diagnostics, modelling and confirmation of existence or non existence of very dense weakly ionised domains in clouds in BLR and NLR regions of AGN has been investigated recently (Srećković et al. 2018). Also the importance of processes (3) for H*(n)+H(1s) collisions, for the principal quantum number $n \geq 4$, in AGN BLR clouds has been investigated too (Srećković et al. 2020). The results (e.g. see data and python scripts for data analysis on https://github.com/sambolino/hexocin) show that the corresponding processes must have influence on the populations of hydrogen highly excited atoms in moderately ionized layers of dense parts of the BLR clouds.

Geo-cosmical plasmas: The $A + RA$ collisions, for the case of alkali metals potentially important for modeling of geo-cosmic weakly ionized plasma have been investigated recently (Ignjatović et al. 2019). The results indicate that the considered processes are factors which influence on the ionization degree and atom excited-state populations in geo-cosmical plasmas. Fig 3 shows $A + RA$ collisions rate coefficient for cases $Li^*(n) + Na$, $Li^*(n) + Li$ and $Na^*(n) + Na$ for modeled atmospheres of Io.

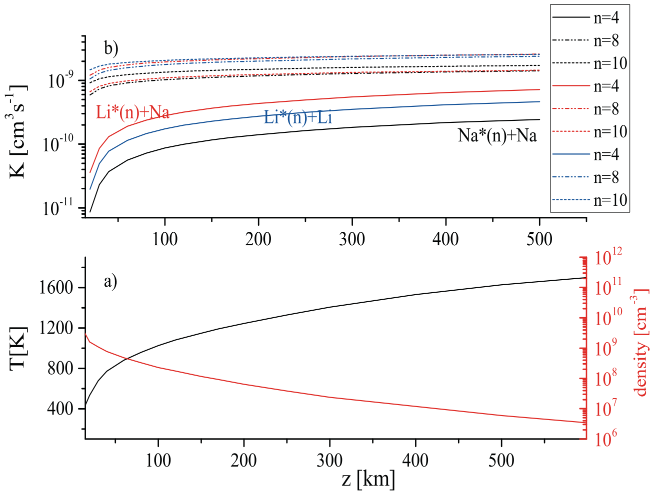

Figure 3: a) Temperature and density altitude profiles for low-density Io model atmosphere; b) Total rate coefficient in $A + RA$ collisions for the low density model atmosphere of Io.

White dwarfs modeling: The influence of considered $A + RA$ processes in the reference to the other ionization and excitation processes was examined in the photospheres of the DB white dwarfs with 12000 K $\leq T_{eff} \leq$ 20000 K. On the basis of the data from model it was established that in the parts of photosphere (8000 K $\leq T \leq$ 20000 K) these processes dominate over concurrent electron-RA impact processes.

References

Badiei, S., Holmlid, L.: 2002, *Mon. Not. R. Astron. Soc.*, **333**, 2, 360.

Dimitrijević, M. S., Srećković, V. A., Zalam, A. A., Miculis, K., Efimov, D. K., Bezuglov, N. N., Klyucharev, A. N.: 2020, *Contrib. Astron. Obs. Skaln. Pleso*, **50**, 1, 66.

Gnedin, Yu N. et al.: 2009, *New Astron. Rev.* **53**, 7-10, 259.

Ignjatović, L. M., Srećković, V. A., Dimitrijević, M. S.: 2019, *Mon. Not. R. Astron. Soc.*, **483**, 3, 4202.

Marinković, B. P., Jevremović, D., Srećkovic, V. A. et al.: 2017, *Eur. Phys. J. D*, **71**, 158.

Mihajlov, A. A., Srećković, V. A., Ignjatović, L. M., Dimitrijević, M. S.: 2016, *Mon. Not. R. Astron. Soc.*, **458**, 2, 2215.

Mihajlov, A. A., Srećković, V. A., Ignjatović, L. M., Klyucharev, A. N.: 2012, *J. Clust. Sci.*, **23**, 1, 47.

Srećković, V. A., Dimitrijević, M. S., Ignjatović, L. M.: 2018, *Mon. Not. R. Astron. Soc.*, **480**, 4, 5078.

Srećković, V. A., Dimitrijević, M. S., Ignjatović, L. M.: 2020, *Contrib. Astron. Obs. Skaln. Pleso*, **50**, 171.