**Publ. Astron. Obs. Belgrade No. 54 (1996), 35 – 38** *Contributed paper*

# CHEMI-IONIZATION AND CHEMI-RECOMBINATION PROCESSES IN SOLAR AND STELLAR ATMOSPHERES

A. A. MIHAJLOV[1,2], M. S. DIMITRIJEVIĆ[2], Lj. M. IGNJATOVIĆ[1] and M. M. VASILIJEVIĆ[1]

[1]*Institute of Physics, P.O. Box 57, 11001 Belgrade, Yugoslavia*
[2]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*

**Abstract.** Within the semi-classical approximation, chemi-ionization processes during symmetrical atom-Rydberg atom collisions were considered, as well as the inverse chemi-recombination processes during the scattering of free electrons by corresponding collisional ion-atom complexes and molecular ions. It was shown that these processes must be taken into account when modelling the low-temperature layers of solar atmosphere and atmospheres of some helium- rich stars.

In Mihajlov and Janev (1981) and Mihajlov *et al.* (1992) a semi-classical theory of chemi-ionization processes during symmetrical atom-Rydberg atom collisions has been developed, as well as a theory of their inverse chemi-recombination processes during the scattering of free electrons by the collisional quasi-molecular ion-atom complexes and the weakly bound molecular ions. These processes are

$$A^*(n) + A \Rightarrow \begin{cases} A_2^+ + e, \\ A + A^+ + e, \end{cases} \tag{1}$$

and the inverse recombination processes are

$$\left.\begin{array}{l} A_2^+ + e \\ A + A^+ + e \end{array}\right\} \Rightarrow A^*(n) + A, \tag{2}$$

where $A, A^+$ and $A_2^+$ denote atom, atomic ion and molecular ion in the corresponding ground electronic states, $A^*(n)$ - atom in the Rydberg state with the principal quantum number $n$, and $e$ - free electron. $A_2^+$ is taken to be in one of the weakly bound rotational - vibrational states. Then, in Mihajlov *et al.* (1996ab), it was shown that in the nonequilibrium plasmas with the degree of ionization $10^{-2}$, influence of processes (1) and (2) on the populations of the atoms $A^*(n)$ is comparable or even dominant in comparison with the influence of known Bates *et al.* (1962ab) electron-atom ionization processes

$$A^*(n) + e \Rightarrow A^+ + e + e, \tag{3}$$

and the electron-electron-ion recombination processes

$$A^+ + e + e \Rightarrow A^*(n) + e. \qquad (4)$$

Besides the extremely nonequilibrium plasmas, our discussion also refers to the plasmas whose state, in relation to many parameters, can be treated as the state of LTE, but where the populations of atoms $A^*(n)$ are still quite different from the equilibrium ones. Here, we have in mind on the the equilibrium populations determined for the given temperature $T$ and the given concentrations of electrons and ions $A^+$. These are just the plasmas that we encounter at considering of the weakly ionized layers in the outer regions of different stellar atmospheres, where the deviations of the populations of the excited atoms $A^*(n)$ from their equilibrium values are caused by the absence of equilibrium between the atomic component of the stellar atmosphere and the radiation. Certain layers in the outer region of the solar atmosphere, as well as in the outer regions of the atmospheres of some helium-rich stars (DB white dwarfs), for which the relevant data on their optical depths exist (Vernazza *et al.* 1981, Koester 1980), fall into this group. In accordance with the present discussion, it is clear that in the case of these layers, the role of the processes (1) and (2), for $A = H$ or $A = He$, can be of great importance. Concretely, the relative importance of these processes, compared with the processes (3) and (4), depends on the behaviour of the ratios

$$I^{(1)}_{i;n}(h)/I^{(3)}_{i;n}(h),$$

$$I^{(2)}_{r;n}(h)/I^{(4)}_{r;n}(h),$$

where $I^{(1)}_{i;n}(h)$ and $I^{(2)}_{r;n}(h)$ denote the ionization and recombination fluxes caused by the chemi-ionization processes (1) and the chemi-recombination processes (2), $I^{(3)}_{i;n}(h)$ and $I^{(4)}_{r;n}(h)$ denote the ionization and recombination fluxes caused by the concurrent processes (3) and (4), and $h$ is the corresponding height. By the definition, these fluxes are given by the expressions

$$I^{(1)}_{i;n}(h) = K^{(1)}_i(T(h))N(A^*(n);h)N(A;h),$$
$$I^{(2)}_{r;n}(h) = K^{(2)}_r(T(h))N(e;h)N(A^+;h)N(A;h),$$
$$I^{(3)}_{i;n}(h) = K^{(3)}_i(T(h))N(A^*(n);h)N(e;h)),$$
$$I^{(4)}_{r;n}(h) = K^{(4)}_r(T(h))N(A^+;h)N(e;h)N(e;h),$$

where $K^{(1)}_i(T)$ and $K^{(2)}_r(T)$ represent the semi-classical rate coefficients for the processes (1) and (2), and they are given in Mihajlov *et al.* (1996ab), while $K^{(3)}_i(T)$ and $K^{(4)}_r(T)$ represent the rate coefficients for the processes (3) and (4) which are given in Vriens and Smeets (1980). Here, by $T(h)$, $N(A^*(n);h)$, $N(A;h)$, $N(A^+;h)$ and $N(n;h)$ we have denoted temperatures and concentrations of the atoms $A^*(n)$, atoms $A$, ions $A^+$ and the electrons on the height $h$, respectively.

On the quantitative level, importance of the processes (1) and (2) can be directly verified on the basis of standard chromospheric model (model C in Vernazza *et al.* 1981), where all the data needed for the calculation of the ionization and recombination fluxes (as the functions of $h$), for $n \leq 8$, are given. The deviations of the atoms $H^*(n)$ populations from the equilibrium values are illustrated in the Table 1, where the values of the quantity $1 - N_{eq}(H^*(n);h)/N(H^*(n);h)$ are given, and $N_{eq}(H^*(n);h)$ represents the equilibrium concentration of the atoms $H^*(n)$. Table 2 shows the behaviour of the ratio of the ionization fluxes $I^{(1)}_{i;n}(h)/I^{(3)}_{i;n}(h)$ as the function of $h$. This Table clearly shows that the influence of the processes (1), in the wide range of $h$, is comparable or even dominant in comparison with the processes (3). Our calculations show that, in the case of solar photosphere, similar situation exists for the processes (2) and (4).

**Table 1.** Values of ratio $1 - N_{eq}(H^*(n);h)/N(H^*(n);h)$

| h(km) | T(K) | n | | | | |
|---|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 7 | 8 |
| 755 | 5280 | .0425 | -.0475 | -.0751 | -.1237 | -.1250 |
| 705 | 5030 | -.0681 | -.1370 | -.1537 | -.2021 | -.2018 |
| 655 | 4730 | -.2483 | -.2694 | -.1697 | -.3087 | -.3057 |
| 605 | 4420 | -.4810 | -.4277 | -.3880 | -.4324 | -.4255 |
| 555 | 4230 | -.6155 | -.5014 | -.4418 | -.4881 | -.4804 |
| 515 | 4170 | -.6143 | -.4826 | -.4223 | -.4716 | -.4646 |
| 450 | 4220 | -.4527 | -.3504 | -.3079 | -.3593 | -.3549 |
| 350 | 4465 | -.1739 | -.1348 | -.1189 | -.1677 | -.1665 |
| 250 | 4780 | -.0234 | -.0140 | -.0103 | -.0550 | -.0551 |
| 150 | 5180 | .0313 | .0382 | .0382 | -.0027 | -.0033 |
| 100 | 5455 | .0282 | .0419 | .0426 | .0042 | .0035 |
| 50 | 5840 | .0266 | .0254 | .0400 | .0039 | .0034 |
| 0 | 6420 | .0188 | .0347 | .0353 | .0029 | .0024 |
| -25 | 6910 | .0165 | .0316 | .0325 | .0022 | .0016 |
| -50 | 7610 | .0158 | .0294 | .0300 | .0024 | .0021 |
| -75 | 8320 | .0152 | .0278 | .0283 | .0030 | .0027 |

Table 2. Value of ratio $I_{i;n}^{(1)}(h)/I_{i;n}^{(3)}(h)$

| h(km) | T(K) | n | | | | |
|---|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 7 | 8 |
| 755 | 5280 | .1187E+02 | .2317E+01 | .6442E+00 | .2263E+00 | .9374E−01 |
| 705 | 5030 | .2243E+02 | .4298E+01 | .1182E+01 | .4130E+00 | .1702E+00 |
| 655 | 4730 | .3662E+02 | .6848E+01 | .1857E+01 | .6430E+00 | .2636E+00 |
| 605 | 4420 | .4803E+02 | .8727E+01 | .2328E+01 | .7978E+00 | .3249E+00 |
| 555 | 4230 | .5479E+02 | .9761E+01 | .2574E+01 | .8761E+00 | .3553E+00 |
| 515 | 4170 | .5860E+02 | .1037E+02 | .2724E+01 | .9252E+00 | .3747E+00 |
| 450 | 4220 | .6084E+02 | .1083E+02 | .2853E+01 | .9708E+00 | .3936E+00 |
| 350 | 4465 | .5857E+02 | .1069E+02 | .2858E+01 | .9811E+00 | .4000E+00 |
| 250 | 4780 | .5297E+02 | .9948E+01 | .2705E+01 | .9378E+00 | .3848E+00 |
| 150 | 5180 | .4341E+02 | .8412E+01 | .2330E+01 | .8161E+00 | .3376E+00 |
| 100 | 5455 | .3536E+02 | .6985E+01 | .1956E+01 | .6899E+00 | .2866E+00 |
| 50 | 5840 | .2266E+02 | .4583E+01 | .1301E+01 | .4629E+00 | .1934E+00 |
| 0 | 6420 | .8895E+01 | .1855E+01 | .5362E+00 | .1929E+00 | .8120E−01 |
| −25 | 6910 | .3826E+01 | .8153E+00 | .2388E+00 | .8664E−01 | .3666E−01 |
| −50 | 7610 | .1262E+01 | .2762E+00 | .8211E−01 | .3010E−01 | .1282E−01 |
| −75 | 8320 | .4806E+00 | .1076E+00 | .3247E−01 | .1200E−01 | .5142E−02 |

## References


Bates, D. R., Kingston, A. E. and McWhirter, R. W. P.: 1962a, *Proc. Roy. Soc.* **A267**, 297.

Bates, D. R., Kingston, A. E. and McWhirter, R. W. P.: 1962b *Proc. Roy. Soc.* **A270**, 155.

Koester, D.: 1980, *Astron. Astrophys.*, **39**, 401.

Mihajlov, A. A., Dimitrijević, M. S. and Djurić, Z.: 1996a, *Physica Scripta,* **53**, 159.

Mihajlov, A. A., Djurić, Z. and Dimitrijević, M. S.: 1996b, *J. Quant. Spectrosc. Radiat. Transfer* **55**, 141.

Mihajlov, A. A. and Janev, R. K.: 1981, *J. Phys. B.*, **14**, 1639.

Mihajlov, A. A., Ljepojević, N. N. and Dimitrijević, M. S.: 1992, *J. Phys. B: At. Mol. Opt. Phys.* **25**, 5121.

Vernazza, J. E., Avrett, E. H. and Loeser, R.: 1981, ApJS **45**, 635.

Vriens, L. and Smeets, A. H. M.: 1980, *Phys. Rev.* **A22**, 940.