Astronomical and Astrophysical Transactions, 1999,
Vol. 18, pp. 145–149
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CHEMI-IONIZATION AND CHEMI-RECOMBINATION PROCESSES IN ASTROPHYSICAL PLASMAS

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(Received September 25, 1996)

Within the semiclassical 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 the solar atmosphere and the atmospheres of some helium-rich stars.

KEY WORDS Chemi-ionization, chemi-recombination, solar atmosphere

In the present paper we will consider the role and importance of chemi-ionization processes during symmetrical-atom–Rydberg-atom collisions:

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

as well as the inverse chemi-recombination processes during the scattering of free electrons by corresponding collisional ion–atom complexes and molecular ions:

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

where A, A^+ and A_2^+ denote an atom, atomic ion and molecular ion in the corresponding ground electronic states, $A^*(n)$ is an atom in the Rydberg state with the principal quantum number n, and e is a free electron. A_2^+ is taken to be in one of the weakly bound rotation–vibrational states.

These processes will be described within the semiclassical approach. It was shown that these processes must be taken into account when modelling the low-temperature layers of the solar atmosphere and atmospheres of some helium-rich stars.

In previous papers (Mihajlov and Janev, 1981; Mihajlov and Ljepojević, 1982; Mihailov *et al.*, 1992) a semiclassical theory of chemi-ionization processes (1) during symmetrical-atom–Rydberg-atom collisions was developed, as well as a theory of their inverse chemi-recombination processes (2) during the scattering of free electrons by the collisional quasimolecular ion–atom complexes and weakly bound molecular ions.

Then, (Mihajlov *et al.*, 1996a, b) it was shown that in non-equilibrium plasmas with the degree of ionization 10^{-2}, the 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.*, 1962a, b) electron–atom ionization processes

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

and the electron–electron–ion recombination processes

$$A^+ + e + e \Rightarrow A^*(n) + e. \tag{4}$$

Besides extremely non-equilibrium plasmas, our discussion also refers to plasmas whose state, by many parameters, can be treated as an LTE state, but where the populations of atoms $A^*(n)$ are still quite different from the equilibrium populations. Here, we think of 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 during consideration 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. Based on what we said 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

$$F_{i;n}(h) = I^{(1)}_{i;n}(h)/I^{(3)}_{i;n}(h), \tag{5}$$

$$F_{r;n}(h) = I^{(2)}_{r;n}(h)/I^{(4)}_{r;n}(h), \tag{6}$$

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 definition, these fluxes are given by the expressions

$$I^{(1)}_{i;n}(h) = K^{(1)}_i(T(h))N(A^*(n);h)N(A;h), \tag{7}$$

$$I^{(2)}_{r;n}(h) = K^{(2)}_r(T(h))N(e;h)N(A^+;h)N(A;h), \tag{8}$$

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

		n				
h (km)	$T(K)$	4	5	6	7	8
755	5280	0.0425	–0.0475	–0.0751	–0.1237	–0.1250
705	5030	–0.0681	–0.1370	–0.1537	–0.2021	–0.2018
655	4730	–0.2483	–0.2694	–0.1697	–0.3087	–0.3057
605	4420	–0.4810	–0.4277	–0.3880	–0.4324	–0.4255
555	4230	–0.6155	–0.5014	–0.4418	–0.4881	–0.4804
515	4170	–0.6143	–0.4826	–0.4223	–0.4716	–0.4646
450	4220	–0.4527	–0.3504	–0.3079	–0.3593	–0.3549
350	4465	–0.1739	–0.1348	–0.1189	–0.1677	–0.1665
250	4780	–0.0234	–0.0140	–0.0103	–0.0550	–0.0551
150	5180	0.0313	0.0382	0.0382	–0.0027	–0.0033
100	5455	0.0282	0.0419	0.0426	0.0042	0.0035
50	5840	0.0266	0.0254	0.0400	0.0039	0.0034
0	6420	0.0188	0.0347	0.0353	0.0029	0.0024
–25	6910	0.0165	0.0316	0.0325	0.0022	0.0016
–50	7610	0.0158	0.0294	0.0300	0.0024	0.0021
–75	8320	0.0152	0.0278	0.0283	0.0030	0.0027

$$I_{i;n}^{(3)}(h) = K_i^{(3)}(T(h))N(A^*(n);h)N(e;h), \tag{9}$$

$$I_{r;n}^{(4)}(h) = K_r^{(4)}(T(h))N(A^+;h)N(e;h)N(e;h), \tag{10}$$

where $K_i^{(1)}(T)$ and $K_r^{(2)}(T)$ represent the semiclassical rate coefficients for the processes (1) and (2), and are given in the papers by Mihailov *et al.*, 1992; Mihailov *et al.*, 1996b), $K_i^{(3)}(T)$ and $K_r^{(4)}(T)$ represent the rate coefficients for the processes (3) and (4) which are given by 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 the temperatures and concentrations of the atoms $A^*(n)$, atoms A, ions A^+ and the electrons on the height h, respectively.

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

The results presented in Tables 1–3 have been determined on the basis of tables related to Model C by Vernazza *et al.* (1981) where the densities of atoms in states with the principal quantum numbers from 1 up to 8 are given as functions of height, and where the temperature and ion and electron densities are given as well.

Table 2. Values of the quantity $F_{i;n}(h)$

		n				
h (km)	$T(K)$	4	5	6	7	8
755	5280	0.1187E + 02	0.2317E + 01	0.6442E + 00	0.2263E + 00	0.9374E − 01
705	5030	0.2243E + 02	0.4298E + 01	0.1182E + 01	0.4130E + 00	0.1702E + 00
655	4730	0.3662E + 02	0.6848E + 01	0.1857E + 01	0.6430E + 00	0.2636E + 00
605	4420	0.4803E + 02	0.8727E + 01	0.2328E + 01	0.7978E + 00	0.3249E + 00
555	4230	0.5479E + 02	0.9761E + 01	0.2574E + 01	0.8761E + 00	0.3553E + 00
515	4170	0.5860E + 02	0.1037E + 02	0.2724E + 01	0.9252E + 00	0.3747E + 00
450	4220	0.6084E + 02	0.1083E + 02	0.2853E + 01	0.9708E + 00	0.3936E + 00
350	4465	0.5857E + 02	0.1069E + 02	0.2858E + 01	0.9811E + 00	0.4000E + 00
250	4780	0.5297E + 02	0.9948E + 01	0.2705E + 01	0.9378E + 00	0.3848E + 00
150	5180	0.4341E + 02	0.8412E + 01	0.2330E + 01	0.8161E + 00	0.3376E + 00
100	5455	0.3536E + 02	0.6985E + 01	0.1956E + 01	0.6899E + 00	0.2866E + 00
50	5840	0.2266E + 02	0.4583E + 01	0.1301E + 01	0.4629E + 00	0.1934E + 00
0	6420	0.8895E + 01	0.1855E + 01	0.5362E + 00	0.1929E + 00	0.8120E − 01
−25	6910	0.3826E + 01	0.8153E + 00	0.2388E + 00	0.8664E − 01	0.3666E − 01
−50	7610	0.1262E + 01	0.2762E + 00	0.8211E − 01	0.3010E − 01	0.1282E − 01
−75	8320	0.4806E + 00	0.1076E + 00	0.3247E − 01	0.1200E − 01	0.5142E − 02

Table 3. Values of the quantity $F_{r;n}(h)$

		n				
h (km)	$T(K)$	4	5	6	7	8
755	5280	0.5975E + 01	0.1166E + 01	0.3243E + 00	0.1139E + 00	0.4718E − 01
705	5030	0.1129E + 02	0.2163E + 01	0.5951E + 00	0.2078E + 00	0.8566E − 01
655	4730	0.1843E + 02	0.3447E + 01	0.9348E + 00	0.3236E + 00	0.1326E + 00
605	4420	0.2418E + 02	0.4393E + 01	0.1172E + 01	0.4015E + 00	0.1635E + 00
555	4230	0.2758E + 02	0.4913E + 01	0.1296E + 01	0.4410E + 00	0.1788E + 00
515	4170	0.2950E + 02	0.5220E + 01	0.1371E + 01	0.4657E + 00	0.1886E + 00
450	4220	0.3063E + 02	0.5449E + 01	0.1436E + 01	0.4886E + 00	0.1981E + 00
350	4465	0.2948E + 02	0.5380E + 01	0.1439E + 01	0.4938E + 00	0.2013E + 00
250	4780	0.2666E + 02	0.5007E + 01	0.1361E + 01	0.4720E + 00	0.1937E + 00
150	5180	0.2185E + 02	0.4234E + 01	0.1173E + 01	0.4107E + 00	0.1699E + 00
100	5455	0.1780E + 02	0.3516E + 01	0.9845E + 00	0.3472E + 00	0.1443E + 00
50	5840	0.1141E + 02	0.2307E + 01	0.6549E + 00	0.2330E + 00	0.9734E − 01
0	6420	0.4478E + 01	0.9335E + 00	0.2699E + 00	0.9710E − 01	0.4087E − 01
−25	6910	0.1926E + 01	0.4103E + 00	0.1202E + 00	0.4360E − 01	0.1845E − 01
−50	7610	0.6350E + 00	0.1390E + 00	0.4132E − 01	0.1515E − 01	0.6454E − 02
−75	8320	0.2419E + 00	0.5416E − 01	0.1634E − 01	0.6038E − 02	0.2588E − 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. and Janev, R. K. (1981) *J. Phys. B.* **14**, 1639.

Mihajlov, A. A. and Ljepojević, N. N. (1982) Proc. Symp. on Physics of Ionized Gases (Dubrovnik, 1982), (Zagreb: Institute of Physics of the University of Zagreb), Contributed papers, p. 385.

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

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.

Vernazza, J. E., Avrett, E. H., and Loeser, R. (1981) *Astrophys. J. Suppl. Ser.* **45**, 635.

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