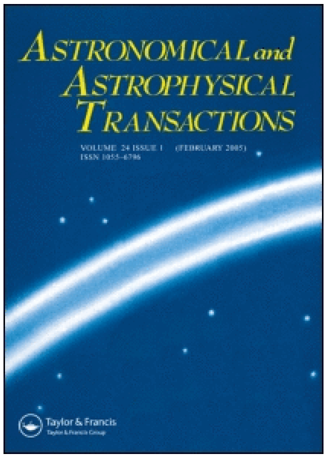

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THE EFFECTS OF PLASMA MICROFIELD DISTRIBUTIONS AND IONIZATION POTENTIAL LOWERING ON THE OPACITY AND SPECTRA OF RADIATION FROM PHOTOSPHERES OF COOLING NEUTRON STARS

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An approximate method is presented for computing the ionization equilibrium and opacities in the photospheres of cooling neutron stars. The method is based on occupation probability formalism which describes the lowering of the ionization potential due to plasma microfield effect. The approach is simple and reproduces rather accurately the results of a more selfconsistent and sophisticated Hummer–Mihalas theory for a low-temperature and high-density H–He plasma. It is shown that the opacities and spectra of radiation outgoing from the photospheres of cooling neutron stars are insensitive to the type of the microfield distribution, and to the method of including the ionization potential lowering, as long as the neutron star effective temperatures $T_{\rm eff} \gtrsim 10^5$ K.

KEY WORDS Ionization, neutron stars

1. INTRODUCTION

Theoretical investigations of thermal evolution of neutron stars (NS) reveal that cooling of NSs depends strongly on the structure of the superdense matter in the NS interiors (e.g., Van Riper, 1991). Recent detections of thermal-like radiation from some radio pulsars (Ögelman, 1991; Finley *et al.*, 1992) give a possibility to compare the theoretical predictions with observational data. This is important for the NS physics and can provide new information on the properties of the superdense matter (equation of state, etc). For interpreting the observational data, one should take into account that thermal spectra emitted from NS surfaces can strongly deviate from the black-body one due to the presence of thin photospheric layers (Romani, 1987). Numerical simulations of the NS photosphere are complicated due to high surface gravity ($g \sim 10^{14}$–10^{15} cm/s^2) and density (up to ~ 10 g/cm^3 at unit optical depth) of the NS surface layers. At these conditions, the ionization equilibrium and radiative opacities may be strongly affected by non-ideality, degeneracy and pressure ionization effects.

A selfconsistent method for including these effects has been developed recently by Hummer and Mihalas (1988, hereafter HM). The method is based on a numerical free-energy-minimization procedure and the occupation probability formalism for truncating the internal partition functions of ions. Substantial deviations from the ordinal Saha equilibrium have been found for the H–He plasma with temperatures ($T \lesssim 10^6$ K) and densities ($\rho \lesssim 10\,\mathrm{g/cm^3}$) appropriate to the photospheres of cooling NSs (Mihalas, Däppen and Hummer, 1988; hereafter MDH). The above procedure is, however, too cumbersome and time-consuming to be used in the photospheric models.

In this paper we show that the mere insertion of the occupation probabilities into the ordinary Saha equations reproduces quantitatively the MDH results for the H–He plasma. This allows one to simplify the computations of the ionization equilibrium and opacities.

2. MODIFICATION OF THE SAHA EQUATIONS AND OPACITIES BY PLASMA MICROFIELDS

The internal partition function Z of an isolated atom is

$$Z = \sum_{i=1} g_i \exp\left(-\frac{\varepsilon_i}{kT}\right), \tag{1}$$

where ε_i is the (unperturbed) ionization potential of the ith level ($i = 1$ corresponds to the ground level), and g_i is the level degeneracy. Interaction of the atom with electric plasma microfields, produced by nearby charged particles, can be described in terms of the lowering of the atomic ionization potential: $\tilde{\varepsilon}_i = \varepsilon_i + \Delta u$. In this case $\Delta u = 2\sqrt{Fze^3}$ is the saddle point value of the electric potential composed of the Coulomb potential of the given ion with the charge number z and the potential produced by nearby particles; $F = \beta F_0$ is an electric micrifield of nearby particles, $F_0 = 2.6\bar{z}eN^{2/3}$ is the mean inter-ion field, $\bar{z}$ is the average charge number of the plasma ions, and N is the number density of the ions (see, e.g., HM). Replacing ε_i by $\tilde{\varepsilon}_i$ in Eq. (1) and averaging over a microfield distribution function $P(\beta)$, we obtain

$$\tilde{Z} = \sum_{i=1} g_i \int_0^{\beta_i^{\mathrm{cr}}} d\beta P(\beta) \exp\left(-\frac{\tilde{\varepsilon}_i}{kT}\right) = \sum_{i=1} g_i W_i \exp\left(-\frac{\varepsilon_i}{kT}\right), \tag{2}$$

$$W_i = \int_0^{\beta_i^{\mathrm{cr}}} d\beta P(\beta) \exp\left(-\frac{\Delta u}{kT}\right),$$

where $\beta_i^{\mathrm{cr}} = F_i^{\mathrm{cr}}/F_0$ corresponds to the critical electric field F_i^{cr} which destroys i-th atomic level and W_i is the occupation probability (to find the ion in the ith state relative to the standard Boltzmann probability). Our definition of W_i differs from that of HM by a factor of $\exp(-\Delta u/kT)$. However, the presence of the latter in our phenomenological approach is physically justified because the factor describes the lowering of the ionization potentials included in the partition function (neglecting the Stark shift and tunneling effect). Specifying $P(\beta)$ and replacing Z by $\tilde{Z}$ in the ordinary Saha equations, we obtain the model equations of the ionization equilibrium with allowance for the inter-particle interactions.

Now consider the opacity. The continuum lowering by the micro-fields allows the photons with energy $E \le |\varepsilon_i|$ to ionize the ith atomic level. A convenient method for calculating corresponding opacities in the framework of the occupation probability formalism has been proposed by Däppen *et al.* (1987). In this approximation, the occupation number N_i of the ith state in the standard equations for the bound-free opacities should be replaced by

$$N_i = N\frac{g_i}{\bar{Z}}\int_{\beta_i^*}^{\beta_i^{\rm cr}} d\beta P(\beta)\exp\left(-\frac{\tilde{\varepsilon}_i}{kT}\right) = \frac{g_i}{\bar{Z}}(W_i - W_i^*)\exp\left(-\frac{\varepsilon_i}{kT}\right), \tag{3}$$

$$W_i^* = \int_0^{\beta_i^*} d\beta P(\beta)\exp\left(-\frac{\Delta u}{kT}\right),$$

where $\beta_i^* \leq \beta_i^{\rm cr}$ corresponds to the electric field at which the continuum lowering Δu allows ionization from the ith state by a photon with energy E. The value of β_i^* is obtained from the equation $E = |\tilde{\varepsilon}_i(\beta_i^*)| = |\varepsilon_i + \Delta u(\beta_i^*)|$ which yields

$$\beta_i^* = \frac{|\varepsilon_i|}{4F_0 z}\left(1 - \frac{E}{|\varepsilon_i|}\right)^2 = \beta_i^{\rm cr}\left(1 - \frac{E}{|\varepsilon_i|}\right)^2. \tag{4}$$

When $E \geq |\varepsilon_i|$, we get $\beta_i^* = W_i^* = 0$. Thus, in our approximation, the opacity produced by the photoionization is obtained by replacing the occupation number for an isolated atom by Eq. (3).

Our modifications of the opacity and Saha equations include the pressure ionization effects in a simplified manner. With increasing density, the inter-ionic

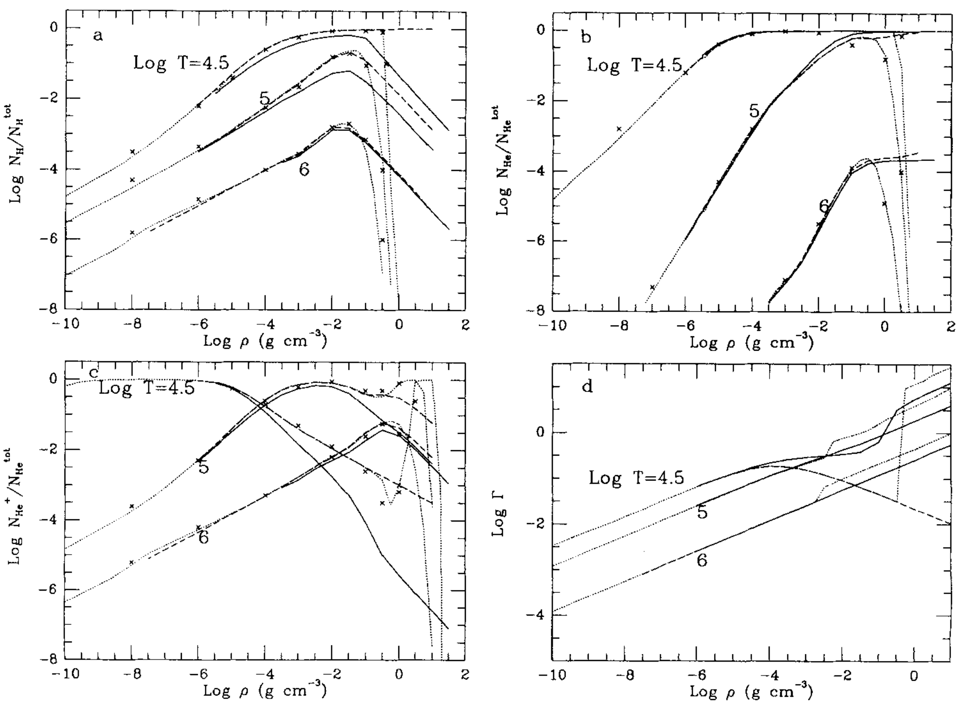

Figure 1 Relative fractions of hydrogen and helium ions (a, b, c), and ion-coupling parameter Γ (d) versus density for H–He plasma (N(He)/N(H) = 0.1) at $T = 10^{4.5}$, 10^5 and 10^6 K. Curves show the modified Saha equilibrium with the H-microfield distribution and the potential lowering Δu in Equation (2) (solid lines), H-distribution and $\Delta u = 0$ (dashes), and NN-distribution and $\Delta u = 0$ (dots). Crosses: MDH results.

microfield F_0 increases, while β_i^{cr} and W_i decrease. Higher atomic bound states are gradually shifted into continuum. Finally the ground states disappear, and the plasma becomes fully ionized even at low temperatures. For low density we have $W_i \to 1$, and all the expressions turn into the standard ideal-gas expressions. Our method is simple but not selfconsistent. A comparison with more selfconsistent methods is required to confirm its validity.

3. RESULTS

Figures 1a–c show numerical results of the ionization equilibrium for the H–He mixture (N(He)/N(H) = 0.1). If we put $\Delta u = 0$ in Eq. (2) and use the modified nearest neighbor (NN) distribution for $P(\beta)$ (used by MDH), our approach reproduces the MDH results. This means that, in the MDH approximation, including the occupation probabilities in the internal partition functions makes a larger effect than allowance for partial degeneracy of electrons and Coulomb correlations in the free energy.

We present also the results obtained with the Holtsmark (H) distribution that describes the effect of distant ions more correctly. This distribution leads to a slower increase of the pressure ionization with increasing density. The difference

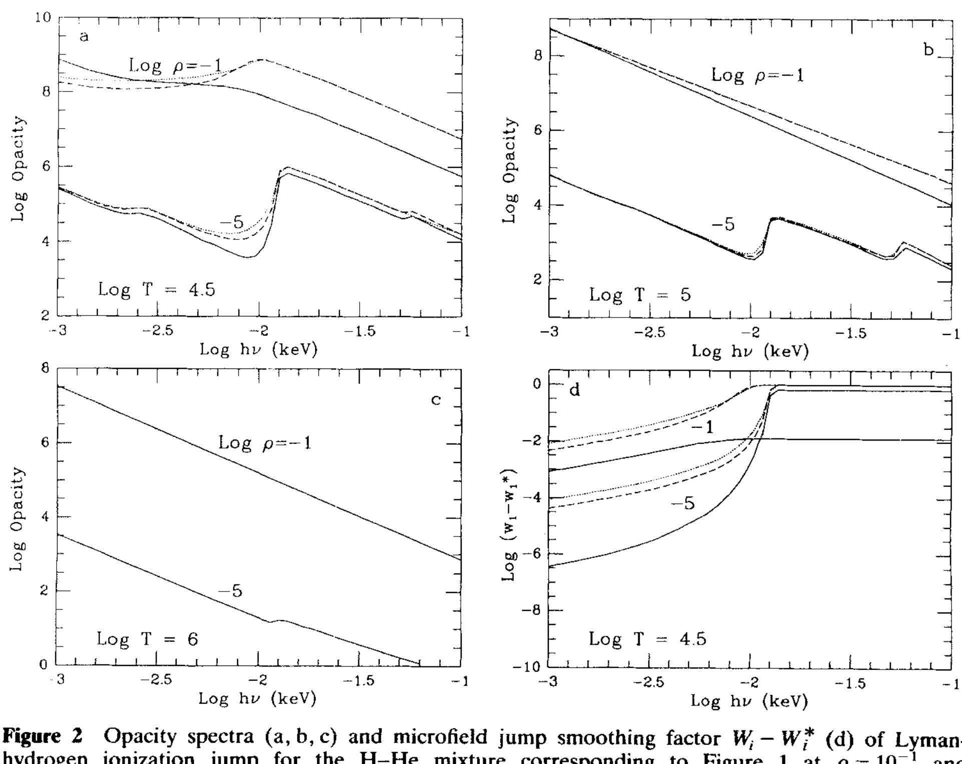

Figure 2 Opacity spectra (a, b, c) and microfield jump smoothing factor $W_i - W_i^*$ (d) of Lyman-hydrogen ionization jump for the H–He mixture corresponding to Figure 1 at $\rho = 10^{-1}$ and 10^{-5} g/cm^3. Solid, dashed and dotted curves have the same meaning as in Figure 1.

between the NN and H cases is explained by exponential damping of the NN-distribution and power-law damping of the H-distribution at $\beta \to 0$ (high densities). In the opposite limit of $\beta \gg 1$ (low densities) both distributions coincide and give the same result. Note that, at high densities, when the energy of the interparticle Coulomb interactions becomes comparable with thermal energy (when the ion-coupling parameter $\Gamma \gtrsim 1$, Figure 1d) both distributions fail and more complicated distributions should be used (see, e.g., Iglesias *et al.*, 1983). According to Figure 1d, one has $\Gamma \lesssim 1$ in a wide range of temperatures and densities appropriate to NS photospheres. Our method of including the potential lowering ($\Delta u > 0$ in Eq. (2)) used with the H-function yields a higher ionization rate in the low-temperature/high-density limit.

Figure 2 shows the opacity spectra (in the Thomson units) that include the free-free and bound-free processes. The ionization jumps are smoothed by plasma microfields. If $\Delta u = 0$, the H and NN-distributions give almost the same opacity. Using the lowering exponential factor with the H-distribution results in sharper jumps at low temperatures and densities (Figure 2a) due to the sharper dependence of $(W_i - W_i^*)$ on $h\nu$ (Figure 2d). However, with increasing density, the jumps are smoothed sooner due to higher ionization (cf. Figures 1 and 2).

Thus, the models of NS photospheres with H–He composition should be

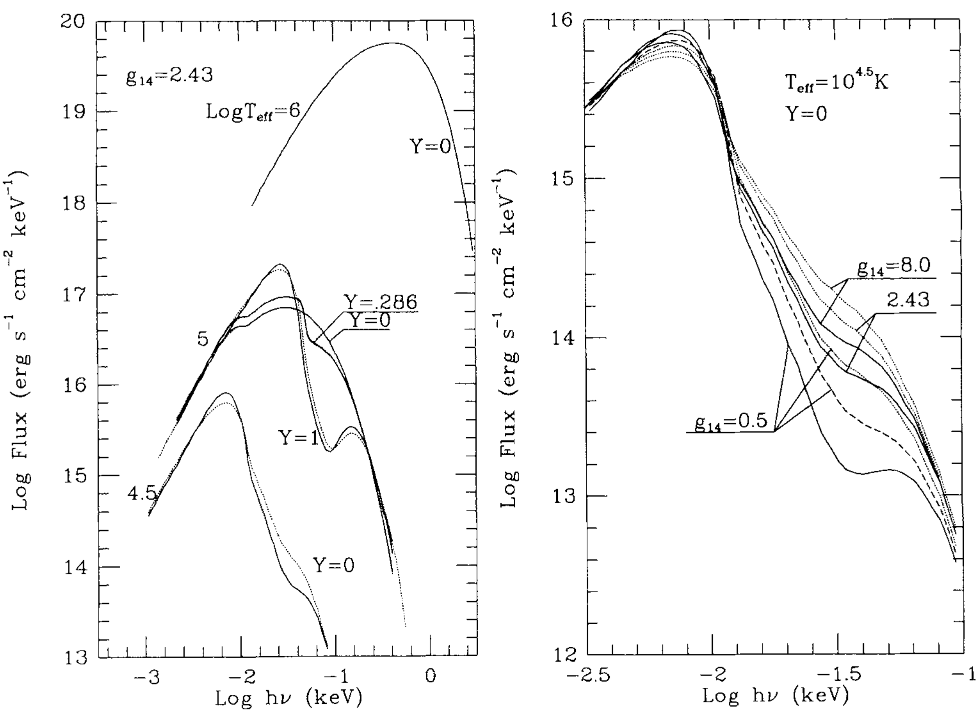

Figure 3 Left (a): Spectra of radiation outgoing from H–He photospheres of cooling NS for the standard surface gravity $g = 2.43 \cdot 10^{14}\,\mathrm{cm/s^2}$, $T_{\mathrm{eff}} = 10^{4.5}$, 10^5 and 10^6 K, and helium abundance $y = 0$, 0.286 and 1. Right (b): Same as on the left-hand side for $y = 0$, $T_{\mathrm{eff}} = 10^{4.5}$ K, and various surface gravities. Solid, dashed and dotted curves have the same meaning as in Figure 1.

insensitive to the type of the microfield distribution and to the method of including the continuum lowering as long as the plasma temperature $T \gtrsim 10^5$ K. Figure 3 shows the spectra of outgoing radiation for photosphere models with various $T_{\rm eff}$ and confirms this conclusion.

The difference of spectra due to different allowance for the ionization potential lowering is visible for the model with $T_{\rm eff} = 10^{4.5}$ K only. Corresponding results are presented in Figure 3b for various surface gravities. The difference in heights and shapes of the hydrogen Lyman-jump is larger for lower surface gravities. It can reach an order of magnitude for every low surface gravities ($g_{14} = 0.5$), when the density at the unit Rosseland depth is low and the difference of opacities is large (cf. Figures 3b and 2a). The difference can be even larger for a photosphere which contains heavier elements. This tendency is seen from Figure 3a (for the purely He composition). For low temperatures and surface gravities, interpretation of observational data under various assumptions on the microfield distributions and potential lowering can lead to different conclusions on the mass-radius relation and/or element abundances. In this case we cannot be certain which model is better. However, from our point of view, the model which uses the H-distribution and includes the ionization potential lowering is preferable. To confirm the validity of our method for modeling and interpretation of the future UV and X-ray observations of thermal radiation from very cool NSs ($T_{\rm eff} \lesssim 10^{4.5}$ K), more sophisticated and selfconsistent methods of opacity computations are required which would take into account the nonideality effects in the equation of state as well as more adequate microfield distributions in dense plasmas.

The present method of including the pressure ionization effects is appropriate for NSs with low magnetic fields ($B \lesssim 10^9$ G, e.g., millisecond radio pulsars). The method can be modified for photospheres of strongly magnetized NSs (Shibanov *et al.*, 1992).

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