A hydrogenic molecular atmosphere of a neutron star

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Abstract

A model of a hydrogenic content of atmosphere of the isolated neutron star 1E1207.4-5209 is proposed. It is based on the assumption that the main component in the atmosphere is the exotic molecular ion \( H_3^{2+} \) and that there exists a magnetic field in the range of \((4 \pm 2) \times 10^{14}\) G. Photoionization \( H_3^{2+} \rightarrow e + 3p \) and photodissociation \( H_3^{2+} \rightarrow H + 2p \) correspond to two absorption features at 0.7 KeV and 1.4 KeV, respectively, discovered by Chandra observatory (Sanwal et al, 2002).

The model predicts one more absorption feature at 80-150 eV corresponding to photodissociation \( H_3^{2+} \rightarrow H_2^{+} + p \).

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A neutron star atmosphere is characterized by strong magnetic fields $\sim 10^{12} - 10^{13}$ G. So far very little is known about its nature. It seems natural to anticipate a wealth of new physical phenomena in such an atmosphere. However, for many years the experimental data did not indicate anything unusual, showing only blackbody radiation. In 2002 the Chandra X-ray observatory collected data on the isolated neutron star 1E1207.4-5209 which led to the discovery of two clearly-seen absorption features at $\sim 0.7$ KeV and $\sim 1.4$ KeV each of them of the width around 100 eV [1] (See Fig.1). Many different proposals about content of the atmosphere were presented, related mostly to atomic ions (for a review, see [1, 2]). In this Note we propose a hydrogenic molecular model.

About 30 years ago it was predicted [3, 4] that in a strong magnetic field unusual chemical systems could appear which do not exist without a strong magnetic field. In [3] (see also [6] and references therein) the hydrogen atom in a strong magnetic field was studied quantitatively with high accuracy. Then in the papers [7] a detailed accurate study of the systems made up of one electron and several protons ($epp\ldots$) under a strong magnetic field in the Born-Oppenheimer approximation was carried out. Let us enlist some conclusions:

- For magnetic fields $B \gtrsim 10^{11}$ G the traditional system $H_2^+$ ($ppe$) exists for moderate inclinations only [12] while a new, exotic system $H_3^{(2+)}$ ($pppe$) appears in linear configuration at zero inclination. Furthermore, for $B \gtrsim 10^{13}$ G another exotic system $H_4^{(3+)}$ ($ppppe$) can appear in linear configuration at zero inclination.

- The neutral system – the Hydrogen atom – has the highest total energy among the one-electron systems, so is the least bound one-electron system for the whole region of magnetic fields studied, $0 < B \lesssim 4.4 \times 10^{13} G$.

- Binding energy of $H$, $H_2^+$, $H_3^{(2+)}$, $H_4^{(3+)}$ increases (when the system exists) with magnetic field growth, while the natural size of the systems $H_2^+$, $H_3^{(2+)}$, $H_4^{(3+)}$ decreases [13]. In particular, for $H_2^+$ and linear $H_3^{(2+)}$ the binding energies at $B \sim 3 \times 10^{13}$ G reach $\sim 700$ eV.

- $H_2^+$ has the lowest total energy for $0 < B \lesssim 10^{13}$ G. However, for $B \gtrsim 10^{13}$ G the exotic system $H_3^{(2+)}$ has the lowest total energy becoming the most bound one-electron system.
In addition it seems natural to assume that for very strong magnetic fields the simplest two-electron molecular system $H_2$ at most has very small binding energy or does not exist due to the repulsive nature of the state formed by two spins 1/2 in triplet configuration. A general review for matter in a strong magnetic field as well as particular consideration about $H_2$ molecule can be found in [8, 9]. Furthermore, in typical neutron star atmospheres the abundance of $H_2$ is smaller than the abundance of $H$ atoms [10].

Let us make the simplest assumption that the atmosphere consists of protons and electrons mostly in a form of the $H, H^+_2, H^{(2+)}_3, H^{(3+)}_4$ systems [11]. It is evident that the charged systems $H^+_2, H^{(2+)}_3, H^{(3+)}_4$ can move mostly in the longitudinal (along the magnetic line) direction, and transverse motion is limited to a domain defined by the Larmor radius. Now, let us consider possible processes which can occur for the systems $H, H^+_2, H^{(2+)}_3, H^{(3+)}_4$. They are divided into three types: ionization (bound-free transitions), dissociation and excitation (bound-bound transitions). Although non-relativistic considerations are justified for $B \lesssim 4.4 \times 10^{13}$ G only, we will do the calculations for higher magnetic fields assuming that we obtain sufficiently correct estimates of energies with error in the binding energies $\lesssim 10\%$ (for a discussion see [9]). These calculations are done using the variational technique with physically relevant trial functions given in [7]. In Table I the binding energies for magnetic fields varying from $2.35 \times 10^{14}$ G to $6 \times 10^{14}$ G are given. It can be seen that the binding energy of the most bound one-electron system $H^{2+}_3$ corresponds to the second absorption feature 1.4 KeV as well as $H^+_2$ (see Fig.1). While the binding energy of the hydrogen atom corresponds to the first absorption feature at 0.7 KeV.

TABLE I: Binding energies in Rydbergs (Ry) and in electron-volts (eV) for different one-electron systems for magnetic fields $(2.35 - 6) \times 10^{14}$ G. Energies in eV are rounded to the nearest integer number ending in 0 or 5.

| $H$-atom | $H^+_2$ | $H^{2+}_3$ | $H^{3+}_4$ |
|----------|--------|------------|------------|
| 47.8 - 57.9 | 83.6 - 104.2 | 89.5 - 114.7 | 74.3 - 98.1 Ry |
| 650 - 790 | 1140 - 1420 | 1220 - 1560 | 1010 - 1335 eV |

In Table II we present the dissociation energies. Surprisingly, two dissociation processes $H^{2+}_3 \rightarrow H + 2p$ and $H^+_2 \rightarrow H + p$ again contribute to the domain corresponding to the first absorption feature at 0.7 KeV. While, the range of sensitivity of the Chandra/ACIS detector
does not allow to see the domain where the process $H_3^{2+} \rightarrow H_2^+ + p$ can contribute.

**TABLE II:** Dissociation energies in Rydbergs (Ry) and electron-volts (eV) for different one-electron systems for magnetic fields $(2.35 - 6.) \times 10^{14} \ G$. Energies in eV are rounded to the nearest integer number ending in 0 or 5.

| Reaction                          | Energies          |
|----------------------------------|-------------------|
| $H_2^+ \rightarrow H + p$        | 35.8 - 46.3 Ry    |
| $H_3^{2+} \rightarrow H + 2p$   | 41.7 - 56.8 Ry    |
| $H_3^{2+} \rightarrow H_2^+ + p$| 5.9 - 10.5 Ry     |
| $H_4^{3+} \rightarrow H + 3p$   | 26.5 - 40.2 Ry    |
|                                  | 490 - 630 eV      |
|                                  | 570 - 770 eV      |
|                                  | 80 - 145 eV       |
|                                  | 360 - 550 eV      |

**TABLE III:** Excitation energies in Rydbergs (Ry) and electron-volts (eV) for different one-electron systems for magnetic fields of $(2.35 - 6.) \times 10^{14} \ G$. Energies in eV are rounded to the nearest integer number ending in 0 or 5.

| Reaction                          | Energies          |
|----------------------------------|-------------------|
| $H_2^+(1\sigma_g \rightarrow 1\pi_u)$ | 18.6 - 21.9 Ry  |
| $H_3^{2+}(1\sigma_g \rightarrow 1\pi_u)$ | 22.4 - 27.9 Ry |
|                                  | 250 - 300 eV      |
|                                  | 305 - 380 eV      |

In Table III we present the energies of the first excitation of $H_2^+$ and $H_3^{2+}$, correspondingly. These processes contribute to the domain which is close to the end of the range of sensitivity of the Chandra/ACIS detector. Also their cross-sections are smaller than photoionization ones [10].

We can formulate our model of the content of the neutron star atmosphere. The description, which we are going to present, appears at magnetic fields of $(4 \pm 2) \times 10^{14} \ G$, of the magnetar strength. We assume that the atmosphere consists mostly of $H_3^{2+}$-ions, which is the most stable one-electron configuration for ultra-high magnetic fields characterized by the smallest total energies comparing with other one-electron systems, with a small abundance of the $H_4^{3+}$-ions [15]. Photoionization of $H_3^{2+}$ may explain the second absorption feature in Fig.1 at around 1.4 KeV [16]. Photodissociation $H_3^{2+} \rightarrow H + 2p$ may give a significant contribution to the first absorption feature at around 730 eV. Secondary photoionization processes of the $H$-atoms produced in $H_3^{2+} \rightarrow H + 2p$ also may contribute to the first absorption feature. Meanwhile, another process of photodissociation of $H_3^{2+} \rightarrow H_2^+ + p$ is not resolved by the Chandra/ACIS detector. However, the secondary processes of (i) pho-
FIG. 1: *Chandra*/ACIS spectrum as presented in [2] (Fig. #1 from [2] by the author’s permission). The solid line is a blackbody model which includes the detector sensitivity to illustrate two absorption features. Domains where the processes $H_3^{2+} \rightarrow e + 3p$ and $H_3^{2+} \rightarrow H + 2p$ contribute are shown by bars. 

Toionization of the $H_2^+$-ions produced contributes to the second absorption feature and (ii) photodissociation $H_2^+ \rightarrow H + p$ contributes to the first absorption feature, while the ternary process of photoionization of $H$-atoms contributes again to the first absorption feature. We neglect contributions coming from electronic excitations of $H_3^{2+}$-ions, in particular those shown in Table III. One of the ways to identify the present model is to study the domain of 80 - 150 eV, which is beyond the *Chandra*/ACIS detector acceptance, where the process $H_3^{2+} \rightarrow H_2^+ + p$ can lead to an absorption feature. Red-shift effects are not taken into account, but they can be included straightforward (see e.g. [1]) and we guess it can increase the magnetic field values for $\sim 20 - 50\%$.

Our magnetic field strengths which correspond to above picture seem to be in contra-
diction with a value independently derived from the neutron star spin parameters (for a discussion see [1]). However, if it is assumed that the magnetic field is produced by an off-centered magnetic dipole as was suggested in [1], the magnetic field strength can reach values of the order of $10^{14}$ G or higher. It is necessary to mention that, recently, XMM-Newton observations [11] confirmed the results of Chandra/ACIS related to absorption features at 0.7 and 1.4 KeV and even indicated the possible existence of the third absorption feature at 2.1 KeV. If the new feature is confirmed it would mean that this feature is outside the range of prediction of the present model and should be explained differently.

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[12] Inclination is defined by the angle between the molecular axis and the magnetic line

[13] Natural size is defined by the distance between end-situated protons

[14] In principle, nuclei can be deuterons or tritons instead of protons.

[15] We neglect temperature and density effects

[16] Ionization means a transition from a discrete spectrum to a continuous one (bound-free transitions). The cross-section of photo-ionization depends on the energy of ionization. Not aware of any reliable calculations of bound-bound and bound-free transitions, even for the simplest molecular system $H_2^+$, we assume, following a detailed study of the hydrogen atom [10],

that (i) photo-ionization cross-section has a maximum near the ionization threshold, and (ii) bound-bound transition amplitudes are small compared to the bound-free ones. We also neglect any difference between ionization threshold (binding energy) and the maximum of the energy distribution, assuming that this difference is small.