NEW CHANNEL FOR THE PHOTOIONIZATION OF HYDROGEN ATOMS IN THE SOLAR SYSTEM

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ABSTRACT

A new two step channel for the photoionization of hydrogen atoms in interplanetary space is proposed. Hydrogen atoms are excited by photons, then decay to the metastable H(2S) state, where they can be photoionized. Competing processes are considered, and the photoionization rate through the proposed indirect channel is calculated. This rate becomes higher than that of direct photoionization for the region closer than 0.4 a.u. to the Sun.

INTRODUCTION

The ionization rate is one of the key parameters in models describing neutral hydrogen atom populations inside of the heliosphere. The study of such populations provides an opportunity to get information on global heliospheric structure, and to derive physical parameters of interplanetary dust and interstellar gas, as well as planetary upper atmospheres and exospheres. Two major processes are believed to determine the ionization rate of the neutral atoms: i) ionization by solar photons, and ii) charge exchange with solar wind ions.

The Sun radiates intense Lyman series hydrogen lines. After photoexcitation to the state with the principal quantum number $n>2$, the hydrogen atom may emit a photon and transfer not to the ground state, but to the metastable H(2S) state. It can be shown that both the direct excitation to the metastable state and the ionization of excited atoms by collisions with solar wind plasma ions and electrons, can be neglected /1/. While being in this metastable state, a hydrogen atom may be ionized by solar photons with wavelength shorter than $\lambda = 3646$ Å (which are rather abundant in the solar spectrum). This way of photoionization was never, to my knowledge, taken into account earlier, and the aim of this work is to consider this indirect channel of ionization of hydrogen atoms in interplanetary space.

EXCITATION TO METASTABLE STATE

Intensities of solar Lyman lines decrease rapidly with the increase of photon energy, and, as will be shown, most of the indirect photoionization effect is due to the excitation channel through the H(3P) state. The total intensity of the solar Lyman-β ($\lambda = 1025.7$ Å) line is $E^{0}_{\beta} = 6\ 10^{-2}$ erg/(cm^2 s) at Earth orbit /2/ (index "0" will correspond to value at Earth orbit). To assess the line width, let us assume that the same atoms that emit in Lyman-α ($\lambda = 1215.6$ Å) are responsible for the Lyman-β emission. The line width is determined by the Doppler shifts due to velocities of individual atoms, so that the ratio $\varkappa = \Delta\lambda/\lambda$ has to be constant for both lines. For Lyman-α, the line width is well known $-\Delta\lambda = 0.8$ Å (e.g. /3/), giving $\varkappa = 6.5\ 10^{-4}$. For the hydrogen atom, one can calculate exactly the probability of photoexcitation (e.g. /4/). Taking into account that the probability of H(3P) state transition to H(2S) is 0.118, one finally obtains the excitation rate to the H(2S) state $\beta^{2S}(R) = \beta^{2S}_{0}(R_{0}/R)^{2}$, where $\beta^{2S}_{0} = 4\ 10^{-7}\ s^{-1}$. The similar analysis for solar Lyman-γ line ($\lambda = 972.5$ Å) with energy flux $E^{0}_{\gamma} = 1.5\ 10^{-3}$ erg/(cm^2 s) /2/ shows that the excitation rate for H(2S) through the H(4P) state is $3.2\ 10^{-9}\ s^{-1}$ at Earth orbit, which is much lower than the rate through the H(3P) state. This channel can be therefore safely neglected, as can all other radiation channels.

FATE OF METASTABLE ATOM

Let us consider now what may happen with a metastable hydrogen atom in interplanetary space. First of all, without any external interactions this atom will decay to ground state by emission of two photons at a rate of δ^{d}=8.226 s^{-1}/5/, i.e. with the life time t_d=0.12 s. Collisions with solar wind plasma electrons and ions, as well as interactions with the solar photons, may lead to either ionization of the atom or to a transition to another state which, in turn, may decay to the ground or a metastable state. Also, the decay of metastable atoms can be caused by the solar wind magnetic field.

It can be shown /1/ that the most important effect of the collisions with solar wind protons and electrons is the transition from $2S_{1/2}$ state to the $2P_{1/2}$ or $2P_{3/2}$ states which results in subsequent very fast (1.6 ns) emission of a Lyman-α photon leaving the hydrogen atom in the ground $1S_{1/2}$ state. The solution of the problem of collisionally induced transitions to 2P states of hydrogen atom was given in /6/. Calculations show that for solar wind plasma density n_0=5 cm^{-3}, V_{SW}=400 km/s and $T_e^{o}=10^4$ K one obtaines $\delta_0^{d,e}$=2.9 $10^{-4} s^{-1}$ and $\delta_0^{d,p}$=3.5 $10^{-4} s^{-1}$ for H(2S) depopulation rates due to collisions with electrons and protons of solar wind respectively. Alpha particles constitute approximately 5% of solar wind number density, and the depopulation rate is proportional to the square of the ion charge. Therefore, the total effect of solar wind ions would be 20% more than presented by the value $\delta^{d,p}$.

A magnetic field is frozen into the solar wind plasma and moving relative to the metastable atom, which would then feel the electric field. For small electric fields, the H(2S) decay time, t_E, is well known (e.g. /4/), and $t_E > t_d$ everywhere in the solar wind /1/. Therefore the effect of a magnetic field can be neglected.

Interaction with solar photons may result either in photoionization, including the channel of indirect photoionization of the present work, or in excitation to higher levels of the atom with the subsequent transition to the ground state. The solar spectrum is assumed to be that of a blackbody with temperature T_S=6000 K. We assume here, also, that the solar radiation intensity is inversely proportional to the square of the distance from the Sun without change of spectral properties. Then the photoionization rate of H(2S) atoms would be $\delta^{i,ph}(R) = \delta_0^{i,ph}(R_0/R)^2$ and

$$\delta_0^{i,ph} = \mu c \int_{\omega_0}^{\infty} \sigma(\omega)\, dN_\omega$$

where ω_0=5.16 10^{15} s^{-1} is the threshold circular frequency for the photoionization, c is the velocity of the light, $\mu = I_0/(4\sigma_{SB} T_S^4)$, I_0=1.39 10^6 erg/(cm^2 s) is the solar constant (radiant flux density at 1 a.u.), σ_{SB} is the Stephan-Boltzman constant, $\sigma(\omega)$ is the photoionization cross section, and dN_ω is the photon number density distribution as a function of temperature T_S. For the H(2S) state, the ionization threshold corresponds to wavelength λ=3646 Å. This means that the major role in photoionization is played by the photons from the bulk of the distribution, and not from the far wing which is characterized by relatively large fluctuations in intensity. Therefore the blackbody approximation of the solar spectrum is adequate for the purpose. For the hydrogen atom, the photoionization cross section can be calculated exactly /7/, the value of μ is equal to 0.47 10^{-5}, and one obtains $\delta_0^{i,ph}$=1.06 s^{-1}.

For the excitation of the metastable atom to the H(3P) state, the photon wavelength is λ=6562.8 Å (Balmer Hα line). The solar irradiance in Hα is a Fraunhofer line with deep minimum down to 0.16 of the value of the continuum /8,9/. The continuum solar irradiance is equal to 1.6 10^2 erg/(cm^2 s Å) /10/. The spectral radiation density responsible for the excitation of atoms depends then on the radial velocity of the atoms. For neutral hydrogen atoms originating in outgassing of interplanetary dust, the initial radial velocity is very small since dust particles are moving with almost circular orbits. The life time of atoms as neutrals is also small, which does not allow gravitation and radiation forces to transform the initial velocity to motion in radial direction. Therefore the spectral density for excitation would correspond to the minimum of the Fraunhofer Hα line. For interstellar hydrogen, the spectral density for excitation would be somewhat higher. We assume here that effective solar spectral irradiance is 0.2 of the level of continuum. The H(3P) state with the probability 0.118 returns back to the H(2S) state, and the depopulation rate by Balmer Hα photons is then 1.51 s^{-1} at Earth orbit. A similar analysis shows that the depopulation rate through the excitation to H(4P) state is 0.19 s^{-1} at Earth orbit, verifying that this channel is relatively insignificant. The depopulation rate decreases rapidly with the increase of principal quantum number of excited state, and the excitation to the states with n>4 will be neglected. Then the total depopulation rate of H(2S) state by photoexcitation is $\delta^{d,ph}(R) = \delta_0^{d,ph}(R_0/R)^2$, where $\delta_0^{d,ph}$=1.70 s^{-1}. This value is much higher than corresponding rates due to the interaction with solar wind plasma, and the effect of the latter can be totally neglected.

PHOTOIONIZATION RATE AND DISCUSSION

Let us now summarize the most important processes for indirect photoionization channel:

i) hydrogen atoms are excited to H(2S) state with the rate $\beta^{2S}(R)$;
ii) metastable atoms are spontaneously depopulated to ground state by two photon decay with the constant rate δ^d ;
iii) metastable atoms are depopulated to ground state by interaction with solar photons at a rate $\delta^{d,ph}(R)$;
iv) metastable atoms are ionized by solar photons at rate $\delta^{i,ph}(R)$.

The total photoionization rate, $\eta(R)$, through the indirect channel is then

$$\eta(R) = \beta_0^{2S}\left(\frac{R_0}{R}\right)^2 \frac{\delta_0^{i,ph}}{\delta^d (R/R_0)^2 + \delta_0^{d,ph} + \delta_0^{i,ph}}$$

It is more convenient to consider the dependence on distance from the Sun not of the ionization rates, but the rates multiplied by $(R/R_0)^2$. For such quantities, the radial dependence vanishes when the ionization rates are inversely proportional to the square of the distance from the Sun, as is the case for ionization rates due to both direct photoionization and charge exchange on solar wind ions.

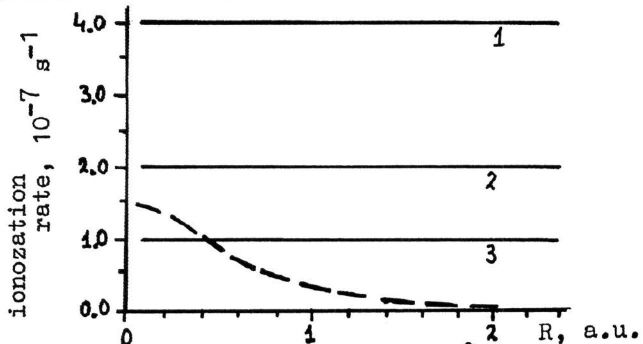

Fig.1. Normalized (multiplied by $(R/R_0)^2$) ionization rates dependences on distance from the Sun. Dashed line - indirect two step photoionization; solid lines - 1) due to charge exchange (at equator), 2) due to charge exchange (at poles), 3) direct photoionization.

The calculated dependence of $\eta^*(R) = \eta(R)\ (R/R_0)^2$ is shown in Figure 1. Also shown are ionization rates corresponding to direct photoionization and charge exchange with solar wind protons. The ionization rates due to charge exchange is believed now to depend strongly on heliographic latitude, its value at equator being twice as large as the value at solar poles /11/. At distances from the Sun of R 1-2 a.u., the ionization rate through the proposed two step channel is proportional to $1/R^4$, and at close approaches, R<0.5 a.u., to $1/R^2$. Here this effect is much more pronounced for neutral hydrogen atoms within Earth orbit, and it vanishes at large distances. At the distance of 1 a.u. from the Sun the proposed channel would add from 8% to 13% to the accepted values of total ionization rates depending on the heliographic latitude. At the distance of 0.42 a.u. from the Sun its effect is equal to the direct photoionization rate, and at closer approaches to the Sun it will add up to 30% at the equator and 50% in polar regions to the accepted values of total ionization rates of hydrogen atoms.

Although the considered effect seems to be too small to result in modifications of interstellar gas properties in Solar system, its influence on the neutral hydrogen atoms outgassing from interplanetary dust grains seems to be significant and must be taken into account. It should be noted that a relatively stronger effect due to the proposed channel can be expected in areas "protected" from solar wind, i.e. inside planetary magnetospheres, particularly for Earth and Venus. It is also interesting to mention that, as estimations show /1/, approximately one hundredth of the sky background far UV radiation is due to the two photon decay of metastable atoms in interplanetary space.

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