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Abstract - Photoionization is one of the key processes which determine the properties of fluxes of neutral atoms in interplanetary space. New two step channel (called indirect) of photoionization of hydrogen atoms is proposed. Hydrogen atoms at first are excited to states with principal quantum number $n > 2$, then decay to metastable H(2S) state, where they can be photoionized. Competing processes due to the interaction with Solar Wind plasma and solar radiation are considered and photoionization rate through the proposed indirect channel is calculated. This rate depends on distance from the Sun as $\propto I/R^4$ at large distances ($R > I - 2$ a.u.) and as $\propto I/R^2$ at close approaches, where it is higher than the rate of direct photoionization.

Аннотация. - Фотоионизация является одним из ключевых процессов, определяющих свойства потоков нейтральных атомов в межпланетном пространстве. Предложен новый двухступенчатый канал фотоионизации. Атомы водорода возбуждаются в состояния с главным квантовым числом $n > 2$, которые распадаются в состояние H(2S), где они могут быть фотоионизованы. Рассмотрены конкурирующие процессы взаимодействия с плазмой солнечного ветра и солнечной радиацией и определена скорость фотоионизации через предложенный канал. Эта скорость зависит от расстояния от Солнца как $\propto 1/R^4$ при больших удалениях ($R \gtrsim$ I-2а.е.) и как $\propto 1/R^2$ вблизи Солнца, где она превосходит величину прямой фотоионизации.

## I. INTRODUCTION

Interplanetary space is filled with dilute neutral gas-mostly hydrogen and helium atoms. There are two major sources of neutral atoms: i) local interstellar medium (LISM), and ii) outgassing of interplanetary dust. The influx of interstellar hydrogen and helium atoms from LISM into Solar System was studied extensively both theoretically and experimentally and the understanding of the major relevant physical processes was achieved (see reviews [I-4] ). Neutral atoms produced by the outgassing of interplanetary dust are confined in the region of the Sun's immediate vicinity within few tenths of a.u. [5,6] . Basic properties of neutral outgassing are not clearly understood and experimental measurements are not numerous [7-9] .

Hydrogen atom ionization rate is one of the key parameters in the models describing neutral atom populations in interplanetary space, as well as in upper atmospheres of planets. The study of such populations gives an opportunity to derive physical parameters of interplanetary dust, interstellar gas, and 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. Since both the solar photon flux and Solar Wind ion flux are usually assumed to be inversely proportional to the square of the distance from the Sun, it is conveniet to introduce ionization rate $\beta_o$ at Earth orbit ($R_o = I$ a.u.) and to scale the ionization rate as $\beta(R) = \beta_o (R_o/R)^2$. The subscript or superscript "$o$" will correspond further for the value at Earth orbit. The accepted values of $\beta$ depend to certain extent on the solar cycle phase and Solar Wind conditions and can be assumed to be on average $\beta_o^{ce} = 4\ IO^{-7}\ s^{-I}$ and

$\beta_0^{ph}$ = I.0 IO$^{-7}$ s$^{-I}$ for charge exchange (at equator) and photoionization rates respectively.

Ionization rate by Solar Wind plasma electrons enhances faster than $1/R^2$ with the approach to the Sun due to electron temperature increase and becomes important at region $R <$ 0.I-0.2 a.u. [3]. In this paper, the electron impact ionization rate will not be considered at all. Solar photon input to ionization rate was assumed earlier to be due to the direct photoionization process of hydrogen atom only

$$\mathrm{H} + \mathrm{ph} \longrightarrow \mathrm{H}^{+} + \mathrm{e} \qquad (\mathrm{I})$$

Here and further on letter "e" designates electron, "ph" - photon, and "p" - proton. However, to photoionize hydrogen atom, there exists another possibility, which we shall call indirect channel. The Sun radiates intensively in Lyman series of hydrogen lines. After photoexcitation to the state with the principal quantum number $n > 2$, the hydrogen atom may emit photon and transfer not to the ground state but to the metastable H(2S) state. The atom can be excited to metastable state also directly by collisions with Solar Wind plasma ions and electrons. While being in this metastable state, hydrogen atom may be ionized by solar photons with the wavelength shorter than $\lambda = 3646$ Å (which are rather abundant in solar spectrum), as well as by collisions with Solar Wind plasma electrons and ions.

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. At first, the rate of excitation of hydrogen atoms to metastable state is calculated. Then the possible fates of such metastable atoms are considered, and finally ionization rate due to the indirect photoionization channel is determined.

## 2. EXCITATION TO H(2S) METASTABLE STATE

Let us consider now the excitation of hydrogen atom, which is in the ground H(IS) state, to metastable H(2S) state. This can happen either due to the interaction with solar photons or due to the collisions with Solar Wind plasma ions and electrons.

The latter process can lead to direct populating of the H(2S) state. The excitation cross-section due to collisions with Solar Wind protons with few kiloelectronvolts energy

$$\mathrm{H(IS)} + \mathrm{p} \longrightarrow \mathrm{H(2S)} + \mathrm{p} \qquad (2)$$

is rather low - typical value for processes of such type is much less than IO$^{-I6}$ cm$^2$ (e.g. [IO]). This value is much lower than the cross section of resonance charge transfer for the same collision partners ( 2 IO$^{-I5}$ cm$^2$ ), which is responsible for the major part of ionization rate $\beta_0^{ce}$. Therefore this collisional excitation can be neglected.

The major component of Solar Wind ions is protons and the presence of ions heavier than protons (mostly alpha particles which constitute 5 % of ion number density) will be neglected if not stated otherwise.

The cross section of excitation due to electron collision

$$\mathrm{H(IS)} + \mathrm{e} \longrightarrow \mathrm{H(2S)} + \mathrm{e} \qquad (3)$$

is less than IO$^{-I7}$ cm$^2$ [II]. This value would correspond to excitation rate less than IO$^{-9}$ s$^{-I}$ at Earth orbit, which is much lower than the value of direct ionization rate and therefore will be neglected. Here and further on Solar Wind electron (proton) number density $n_e(n_p)$ is assumed to be inversely proportional to the square of the distance from the Sun and equal to $n_e^c(n_p^\circ) = 5$ cm$^{-3}$ at Earth orbit.

The Sun radiation in Lyman series of hydrogen lines is absorbed with certain efficiency by hydrogen atoms. Therefore hydrogen atoms can be excitied to the states with the principal quantum numbers $n > 2$ , which may decay, in their turn, to H(2S) state with the emission of the photons

$$\mathrm{H(IS)} + \mathrm{ph} \longrightarrow \begin{cases} \mathrm{H(3P)} \longrightarrow \mathrm{H(2S)} + \mathrm{ph} \\ \mathrm{H(4P)} \longrightarrow \mathrm{H(2S)} + \mathrm{ph} \\ \ldots\ldots \end{cases} \qquad (4)$$

Intensities of solar Lyman lines decrease rapidly with the increase of photon energy, and, as will be shown, the most of the effect is due to the channel through the excitation of H(3P) state. Therefore other possible channels (through excitation of H($n$>3) states)will be neglected.

Total intensity of solar Lyman- $\beta$ ($\lambda$ = I025.7 Å) line is $E_\beta^\circ$ = 6 IO$^{-2}$ erg/(cm$^2$s) at Earth orbit [I2] . To assess the line width, let us assume that the same atoms, that emit in Lyman- $\alpha$ ( $\lambda$ = I2I5.6 Å), are responsible for the Lyman- $\beta$ emission. The line width is determined by the Doppler shifts due to the velocities of individual atoms and then the ratio $\varkappa = \Delta\lambda / \lambda$ has to be constant for the both lines. For Lyman- $\alpha$ , the line width is well known - $\Delta\lambda$= 0.8 Å (e.g. [I3] ) and then $\varkappa$ = 6.5 IO$^{-4}$.

The radiation flux density in the lines is

$$\rho_\omega(R) = \frac{1}{c}\left|\frac{dE}{d\omega}\right| = \frac{1}{c} \cdot \frac{E(R)}{\varkappa\omega} \qquad (5)$$

where $\omega$ is wave circular frequency, $c$ is velocity of the light, and $E(R) = E^\circ (R_\circ/R)^2$ is intensity of solar line.

The probability $P$ to excite hydrogen atom to the state with the principle quantum number $n$ can be calculated exactly [I4] and is equal to

$$P(1,0 \longrightarrow n,1) = A_{10}^{n1} \frac{c^3 \pi^2}{\hbar \omega^3} \rho_\omega \qquad (6)$$

where

$$A_{10}^{n1} = 8\ 10^9 \frac{2^8 n(n-1)^{2n-2}}{3(n+1)^{2n+2}} \text{ s}^{-1} \qquad (7)$$

is the transition probability between ground state ( $n = 1$, $\ell = 0$ ) and state ($n$ , $\ell = 1$). For $n$ = 3, one obtains

$$A_{10}^{31} = 0.5\ 10^9 \text{ s}^{-1}$$

Substituting ( 5 ) and ( 7 ) to ( 6 ), one obtains excitation rate

$$P(1S \rightarrow 3P) = 3.4\ \mathrm{IO}^{-6} \text{ s}^{-\mathrm{I}}$$

for $R = R_\circ$.

The probabilities of H(3P) state subsequent transitions to H(IS) and H(2S) are 0.882 and 0.II8 respectively. Therefore, finally excitation rate to H(2S) state at Earth orbit is

$$\beta_\circ^{2S} = 4\ \mathrm{IO}^{-7} \text{ s}^{-\mathrm{I}}$$

Obviously, the excitation rate depends on distance from the Sun as

$$\beta^{2S}(R) = \beta_\circ^{2S} (R_\circ/R)^2 \qquad (8)$$

The similar analysis for solar Lyman- $\gamma$ line ( $\lambda$ = 972.5 Å) with energy flux $E_\gamma^\circ$ = I.5 IO$^{-3}$ erg/(cm$^2$s) [I2] shows that excitation rate of H(2S) through H(4P) state is 3.2 IO$^{-9}$ s$^{-\mathrm{I}}$ at Earth orbit, which much lower than that through H(3P) state and can be therefore safely neglected as well as all other radiation channels.

## 3. FATE OF H(2S) METASTABLE HYDROGEN ATOM

Let us consider now what may happen with 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 $\delta^{d} = 8.226\ s^{-I}$ [I5], i.e. with the life time 0.I2 s. Corresponding rates for different H(2S) depopulation channels we will denote by symbol $\delta^{d}$ with appropriate additional superscripts. Collisions with Soalr Wind plasma electrons and ions as well as interaction with the solar photons may lead to either ionization of the atom or to transition to another state which eventually may decay to the ground or again metastable state of the atom. Also the decay of metastable atom can be caused by the Solar Wind magnetic field. The major possible channels are the following.

$$\begin{array}{lll}
H(2S) \longrightarrow & H(2S) \longrightarrow H(IS) + ph + ph & (a) \\
\longrightarrow & H(2S) + p, e, ph \longrightarrow H(n>2) + \ldots & \\
 & \qquad \qquad \qquad \longrightarrow H(IS) + ph & (b) \\
 & \qquad \qquad \qquad \longrightarrow H(2S) + ph & (c) \\
\longrightarrow & H(2S) + p, e \longrightarrow H(2P) + \ldots & \qquad (9) \\
 & \qquad \qquad \qquad \longrightarrow H(IS) + ph & (d) \\
\longrightarrow & H(2S) + p, e, ph \longrightarrow H^{+} + \ldots & (e) \\
\longrightarrow & H(2S) + \text{magnetic field} \longrightarrow H(IS) + \ldots & (f)
\end{array}$$

We note that channel (c) leades again to the hydrogen atom in metastable state, and channel (e) corresponds to indirect ionization. At first, the interaction with Solar Wind ions and electrons will be considered, then the effect of magnetic field, and finally the interaction with solar photons.

### 3.I. Collisions with Solar Wind ions and electrons

The major effect of the collisions with Soalr Wind protons and electrons is the transition from $2S_{I/2}$ state to the $2P_{I/2}$ or $2P_{3/2}$ states which results in the subsequent very fast (I.6 ns) emission of Lyman-$\alpha$ photon and hydrogen atom in the ground $IS_{I/2}$ state. The solution for the problem of collisionally induced transitions to 2P states of hydrogen atom was given by [I6].

Thermal velocities of electrons are higher than the bulk velocity of the Solar Wind and hence pure Maxwellian distribution is assumed to be valid. Then, following the formalism of [I6], the depopulation rate of H(2S) state would be

$$\delta^{d,e} = \frac{96\, e^4 a_0^2}{\hbar^2}\left(\frac{\pi m_e}{gKT_e}\right)^{1/2}\left[\ln\left(\frac{0.46\, kT_e^4\, \hbar}{e^2 a_0\, m_e \omega'}\right) + 2\ln\left(\frac{0.46\, kT_e^4\, \hbar}{e^2 a_0 m_e \omega''}\right)\right] \qquad (\text{IO})$$

where $n_e$ - electron number density, $a_0 = \hbar^2/(m_e e^2)$ - Bohr radius, $m_e$ - electron mass, $T_e$ - electron temperature, $\omega'$ and $\omega''$ are circular frequencies corresponding to the energy differencies $\Delta E = \hbar\omega$ between levels $2S_{I/2} - 2P_{I/2}$ ( $\nu' = \omega'/2\pi = I.057\ IO^9$ Hz) and $2S_{I/2} - 2P_{3/2}$ ( $\nu'' = \omega''/2\pi = 9.9I6\ IO^9$ Hz) respectively. Two items of the sum in brackets of formula (IO) correspond to transitions to two levels of H(2P) state, and factor two at the second item being due to the statistical weight of the level $2P_{3/2}$. The value of $\delta^{d,e}$ decreases with the increase of the electron temperature. The electron temperature in the Solar Wind increases with the approach to the Sun, therefore the upper limit on $\delta^{d,e}$ for $R < I$ a.u. can be obtained if one assumes $T_e = T_e^{\circ} = IO^4$ K. The electron (and proton) number density depends on distance from the Sun as

$$n_e(R) = n_e^{\circ}\ (R_0/R)^2 \qquad (\text{II})$$

for $R > 0.05$ a.u. [3] and one obtains

$$\delta^{d,e}(R) = \delta_0^{d,e}\ (R_0/R)^2 \qquad (\text{I2})$$

where depopulation rate at Earth orbit $\delta_o^{d,e} = 2.9\ \mathrm{I0}^{-4}\ \mathrm{s}^{-\mathrm{I}}$. It is important that the value of $\delta^{d,e}$ in ( I2 ) represents the upper limit, and the real values of depopulation rate would be lower.

For Solar Wind protons, the situation is inverse to that of electrons, i.e. thermal velocities are much lower (though increasing with the approach to the Sun) than the bulk velocity. So we will neglect thermal velocities and assume that proton velocity $V_p$ = const = 400 km/s.

Applying the formalism of [I6], one can obtain

$$\delta^{d,p}(R) = \delta_o^{d,p}\,(R_o/R)^2 \qquad (\mathrm{I3})$$

and

$$\delta_o^{d,p} = 2\pi n_p^o\, b^2 V_p \left[3(1.5-2C) + \ln\left(\frac{V_p}{b\omega'}\right) + 2\ln\left(\frac{V_p}{b\omega''}\right)\right] \qquad (\mathrm{I4})$$

where $C = 0.5772...$, and $b^2 = (12 e^4 a_o^2)/(\hbar^2 V_p^2)$

For assumed Solar Wind plasma properties

$$\delta_o^{d,p} = 3.5\ \mathrm{I0}^{-4}\ \mathrm{s}^{-\mathrm{I}}$$

Alpha particles constitute approximately 5% of Solar Wind number density, and the depopulation rate is proportional to the square of the ion charge. Therefore total effect of Solar Wind ions would be 20% more than presented by the value $\delta^{d,p}$.

It should be noted that corresponding effective depopulation cross section

$$\sigma^{d,p} = \delta_o^{d,p}/(n_o^p V_p) = \mathrm{I}.85\ \mathrm{I0}^{-\mathrm{I2}}\ \mathrm{cm}^2$$

is unusually large. Among other channels involving collisions with Solar Wind plasma particles, the largest cross section

characterizes the process of resonance charge exchange

$$\mathrm{H}^+ + \mathrm{H(2S)} \longrightarrow \mathrm{H(2S)} + \mathrm{H}^+ \qquad (\mathrm{I5})$$

Through the cross section for this process is rather high - 60 $\mathrm{I0}^{-\mathrm{I6}}$ cm$^2$ [I7] , it is still uncomparably lower than $\sigma^{d,p}$. Therefore this charge transfer channel and all other possible collisional (with Solar Wind ions and electrons) channels can be ignored.

### 3.2. Effect of magnetic field

Magnetic field $B$ is frozen into Solar Wind plasma and metastable atom would feel the electric field

$$\vec{E} = \frac{1}{c}\,\vec{V}_{sw} \times \vec{B} \qquad (\mathrm{I6})$$

For the small electric fields, H(2S) state life time is determined by the expression [I4]

$$t_E = t_p\,(E/475)^{-2} \qquad (\mathrm{I7})$$

where $E$ is in the units of V/cm, $t_p$=I.6 $\mathrm{I0}^{-9}$ ns is the life time of H(2P) state. Magnetic field decreases with the increase of the distance from the Sun and at Earth orbit $B_o < \mathrm{I0}^{-4}\ G$ . Obviously the most pronounced effect would be in the region close to the Sun. Radial component of magnetic field depends on distance from the Sun roughly as

$$B^r(R) = B_o^r\,(R_o/R)^2 \qquad (\mathrm{I8})$$

At close approaches to the Sun, the magnetic field vector is almost parallel to Solar Wind velocity vector $\vec{V}_{sw}$, i.e. radial component of magnetic field is much greater than other ones. In that case the value of $E$ is much lower (at least one order of magnitude) than the value of $E^* = V_{sw} B^r/c$.

Even for the unrealistically large values of $E^*$, the lifetime of metastable atoms, which is proportional to $R^4$, is much longer than and equals that of for two photon decay only at $R$ = 0.03 a.u. Therefore one can safely neglect effect of interplanetary magnetic field.

### 3.3. Interaction with solar photons

Interaction with solar photons may result either in photoionization (the channel of interest for the present work) or in excitation to higher levels of atom with the subsequent transition to the ground state.

At first we consider the photoionization.

Solar spectrum is assumed to be that of the blackbody with the temperature $T_s$ = 6000 K. We assume here also that 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

$$\delta^{i,ph}(R) = \delta_0^{i,ph}(R_0/R)^2 \qquad ( I9 )$$

and

$$\delta_0^{i,ph} = \mu c \int_{\omega_0}^{\infty} \sigma(\omega)\, dN_\omega \qquad ( 20 )$$

where $\omega_0$ = 5.I6 IO$^{I5}$ s$^{-I}$ - threshold circular frequency for the photoionization, $c$ - velocity of the light, $\mu = I_0/(4\sigma_{SB} T_s^4)$ , $I_0$ = I.39 I0$^6$ erg/(cm$^2$ s) - solar constant (radiant flux density at I a.u.), $\sigma_{SB}$ - Stephan-Boltzman constant, $\sigma(\omega)$ - photoionization cross section, $dN_\omega$ - photon number density distribution.

Misha, take please the unique information:
The polynom Pn for n=1 is equal to 1 (unity).

For blackbody radiation

$$dN_\omega = \frac{1}{\pi^2 c^3}\,\frac{\omega^2\, d\omega}{\exp\left(\frac{\hbar\omega}{kT_s}\right) - 1} \qquad ( 2I )$$

For H(2S) state, the ionization threshold corresponds to wavelength $\lambda$ = 3646 Å. This means that the major role in photoionization is played by the photons from the bulk of the distribution and not from that of 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 hydrogen atom, the photoionization cross section can be calculated exactly, and for atom in the state with the principal quantum number $n$ and nucleous charge $Z$ the cross section is (e.g. [I8] )

$$\sigma(\omega) = \frac{2^6 n^3 \pi \sigma_0}{Z^2 \alpha^3}\,\frac{1}{\gamma^4}\,F_n\left(\sqrt{\gamma - 1}\right) P_n\left(\frac{1}{\gamma}\right) \qquad ( 22 )$$

where $\gamma = \omega/\omega_0$ , $\omega_0$ - threshold circular frequency for photoionization, $\sigma_0 = (8\pi/3)(e^2/m_e c^2)^2$ - Thomson cross section, $\alpha = e^2/\hbar c$ - fine-structure constant,

$$F_n(x) = \frac{\exp\left(-\frac{4n\, \mathrm{arctg}(x)}{x}\right)}{1 - \exp\left(-\frac{2\pi n}{x}\right)} \qquad ( 23 )$$

and $P_n(1/\gamma)$ is a polynom with coefficients determined by the principal quantum number $n$ . For H(2S) state, $n$ = 2 and $P_2(1/\gamma) = -6(1/\gamma) + 8(1/\gamma)^2$ . After substitution of (2I), (22) and (23) to (20) and introduction of

$\xi = \hbar\omega/(kT_s)$ one obtaines for H(2S) state

$$\delta_c^{i,ph} = \frac{2^9 \sigma_c \mathcal{M} \omega_0^4}{\alpha^3 \pi c^2 k T_s} \int_{\xi_0}^{\infty} \frac{F_2(\sqrt{\gamma - 1})\, P_2(1/\gamma)\, d\xi}{\xi^2 (\exp(\xi) - 1)} \qquad (24)$$

where $\xi_0 = \hbar\omega_0/(kT_s) = 6.58$ and $\gamma = \omega/\omega_0 = \xi/\xi_0$ . The value of $\mathcal{M}$ is equal to 0.47 IO$^{-5}$ and the integral in (22) is equal to I.34 IO$^{-7}$. Then

$$\delta_c^{i,ph} = \mathrm{I.06\ s^{-I}}$$

Let us consider now the excitation of hydrogen atom from the metastable state H(2S) . The excitation rate at Earth orbit from level ($n = 2$, $\ell = 0$) to level ($n > 2$, $\ell = \mathrm{I}$) would be

$$P(2,0 \rightarrow n,1) = A_{20}^{n1} \frac{c^3 \pi^2}{\hbar \omega^3} \rho_\omega = A_{20}^{n1} \frac{\lambda^5}{8\pi h c} \rho_\lambda \qquad (25)$$

where $\omega$ and $\lambda$ are circular frequency and wavelength corresponding to the transition, and $\rho_\omega$ and $\rho_\lambda$ - are spectral energy densities. For the excitation to the H(3P) state, the photon wavelength is $\lambda$ = 6562 Å (Balmer $H\alpha$ line), $A_{20}^{31}$ = 6.6 IO$^7$ s$^{-I}$. Irradiance of solar continuum at the vicinity of $H\alpha$ line is I.6 IO$^2$ erg/(cm$^2$ s Å) [I9] . The irradiance in $H\alpha$ is a Fraunhofer line with deep minimum down to 0.I6 of the value of continuum [20,2I] . Spectral radiation density responsible for the excitation of atoms depends then on the radial velocity of the atoms. For neutral hydrogen atoms originated in outgassing of interplanetary dust, the initial radial velocity is very small since dust particles are moving along almost circular orbits and the life time of atoms as neutrals is also small which does not allow to transform the initial velocity to the motion in radial direction. Therefore the spectral density for excitation would correspond to the very minimum of Fraunhofer line. For interstellar hydrogen the spectral density for excitation would be a little bit higher. For exmple, for radial velocity 20 km/s the spectral density would be 0.25 of the level of continuum [2I] . We assume here that effective solar spectral irradiance is 0.2 of the level of continuum and is equal to $(\rho_\lambda c)$ = 0.32 IO$^2$ erg/(cm$^2$ s Å), and excitation rate at Earth orbit is then

$$P(2,0 \rightarrow 3,1) = \mathrm{I.72\ s^{-I}}$$

The H(3P) state with the probability 0.882 decays to the ground state and with the probability 0.II8 returns back to H(2S) state. Thetefore the depopulation rate by Balmer $H\alpha$ photons is

$$\delta_c^{d,ph,n=3} = \mathrm{I.5I\ s^{-I}}$$

For the excitation to H(4P) state, the photon wavelength is $\lambda$ = 486I.3 Å (Balmer $H\beta$ line), $A_{20}^{41}$ = 2.8 IO$^7$ s$^{-I}$. Solar irradiance at Balmer $H\beta$ constitutes at minimum 0.I3 of the continuum level [20,22] , which is equal to 2.I IO$^2$ erg/(cm$^2$ s Å) [I9] . We assume again that effective irradiance at line is 0.2 of the continuum level, and hence $(\rho_\lambda c)$ = 0.42 IO$^2$ erg/(cm$^2$ s Å). The transition probability for H(4P) to return to H(2S) state is 0.I2 . Then the depopulation rate at Earth orbit would be

$$\delta_0^{d,ph,n=4} = \mathrm{0.I9\ s^{-I}}$$

The depopulation rate decreases rapidly with the increase of principal quantum number of the excited state, and the excitation to the states with $n > 4$ will be neglected. Then the total depopulation rate at Earth orbit by photoexcitation of the H(2S) state is

$$\delta_0^{d,ph} = \delta_0^{d,ph,n=3} + \delta_0^{d,ph,n=4} = 1.70 \text{ s}^{-1}$$

This value is much higher than corresponding rates due to the interaction with Solar Wind plasma , and the latter effect can be totally neglected.

## 4. PHOTOIONIZATION RATE

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 depopulated to ground state by two photon decay with the constant rate $\delta^{d}$ ;

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 photoionization rate $\eta(R)$ through indirect channel is then

$$\eta(R) = \beta^{2S}(R)\,\frac{\delta^{i,ph}(R)}{\delta^{d} + \delta^{d,ph}(R) + \delta^{i,ph}(R)} = \beta_0^{2S}\left(\frac{R_0}{R}\right)^2 \frac{\delta_0^{i,ph}}{\delta^{d}\left(\frac{R}{R_0}\right)^2 + \delta_0^{d,ph} + \delta_0^{i,ph}} \tag{26}$$

## 5. DISCUSSION

It is convenient to consider the dependence on distance from the Sun not of the ionization rate but that of multiplied by the $(R/R_0)^2$ . For such values the dependence is constant. If the ionization rate is inversely proportional to the square of the distance from the Sun, which is the case for ionization rates due to direct photoionization process and charge exchange on Solar Wind ions.

The calculated dependence of $\xi^*(R) = \eta(R)\,(R/R_0)^2$ is shown in fig. I. Also are shown ionization rates corres-

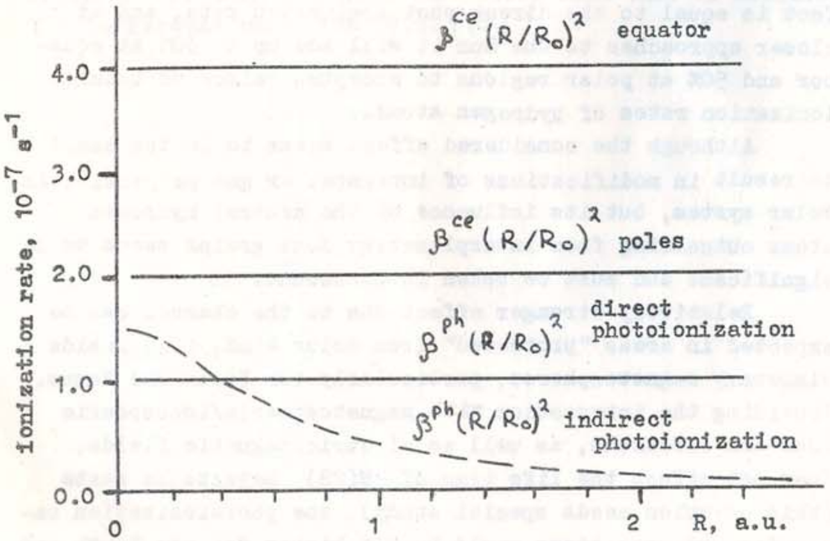

Fig.1. Dependences of photoionization rates on distance from the Sun.

ponding to direct photoionization and charge exchange on Solar Wind protons. Ionization rate due to charge exchange is believed now to depend strongly on heliographic latitude, its value at equator being twice as large as that of at solar poles (e.g. [23] ).

At large distances from the Sun ( R >I-2 a.u.), the ionization rate through proposed two step channel is proportional to $1/R^4$ , and at close approaches - to $1/R^2$ . Hence the effect is much more pronounced for neutral hydrogen atoms within Earth orbit, and it vanishes at large distances. At the distance of Earth orbit from the Sun, the proposed channel would add from 8% to I3% 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 equator and 50% at polar regions to 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, but its influence on the neutral hydrogen atoms outgassing from interplanetary dust grains seems to be significant and must be taken into account.

Relatively stronger effect due to the channel can be expected in areas "protected" from Solar Wind, i.e. inside planetary magnetospheres, particularly for Earth and Venus. Providing the interaction with magnetospheric/ionospheric ions and electrons, as well as electric/magnetic fields, does not affect the life time of H(2S) metastable state (this question needs special study), the photoionization rates for hydrogen atoms would be 40% higher for the Earth and 60% for the Venus.

It is interesting to estimate the level of sky background radiation $I_b$ resulting from the two photon decay of metastable hydrogen atoms. At distances greater than I-2 a.u. from the Sun, almost all metastable atoms decay through this channel. Taking into account that I2% of hydrogen atoms excited by solar radiation to H(3P) state decay to H(2S) metastable state, while 88% to H(IS) state with the emission of Lyman- $\beta$ photons, one can expect that $I_b$ would be roughly 4 times lower than the sky background radiation in Lyman- $\beta$ line.

Background radiation in Ly- $\beta$ constitutes about 2 R [24,25] and hence $I_b$ =0.5 R (I R=$IO^6/4\pi$ ph $cm^{-2}s^{-I}sr^{-I}$). Two photon decay is characterized by a rather broad spectrum of the emitted photons [26] . For the range of maximum spectral density around $\lambda$ = I500 Å , one obtains photon flux 3 $IO^{-4}$ R/Å due to two photon decay. This flux is approximately two orders of magnitude lower than that of measured EUV background radiation (e.g. [27] ).

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