Planet. Space Sci., Vol. 38, No. 10, pp. 1225–1230, 1990
Printed in Great Britain.

0032-0633/90 $3.00+0.00
Pergamon Press plc

TWO-STEP PHOTOIONIZATION OF HYDROGEN ATOMS IN INTERPLANETARY SPACE

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(*Received in final form* 23 *January* 1990)

Abstract—Photoionization is one of the key processes which determine the properties of fluxes of neutral atoms in interplanetary space. A new two-step channel (called indirect) of photoionization of hydrogen atoms is proposed. Hydrogen atoms are at first excited to states with principal quantum number $n > 2$, then decay to metastable H(2S) states, where they can be photoionized. Competing processes due to the interaction with solar wind plasma and solar radiation are considered and the photoionization rate through the proposed indirect channel is calculated. This rate depends on distance from the Sun as $\propto 1/R^4$ at large distances ($R > 1$–2 a.u.) and as $\propto 1/R^2$ at close approaches, where it is higher than the rate of direct photoionization.

1. 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 saturated by solar wind ions. The influx of interstellar hydrogen and helium atoms from LISM into the solar system was studied extensively both theoretically and experimentally and an understanding of the major relevant physical processes was achieved (see reviews of Axford, 1973; Fahr, 1974; Holzer, 1977; and more recently Bertaux, 1984). Neutral atoms produced by the outgassing of interplanetary dust are confined in the region (within a few tenths of astronomical units) of the Sun's immediate vicinity (Banks, 1971; Fahr *et al.*, 1981). Basic properties of neutral outgassing are not clearly understood and experimental measurements are not numerous (Fahr *et al.*, 1980a, b; Fahr and Ripken, 1985).

The hydrogen atom ionization rate is one of the key parameters in the models describing neutral atom populations in interplanetary space. The study of such populations gives an opportunity 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. 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 convenient to introduce an ionization rate β_0 at the Earth orbit ($R_0 = 1$ a.u.) and to scale the ionization rate as $\beta(R) = \beta_0(R_0/R)^2$. The subscript or superscript "0" will correspond further for the value at Earth orbit. The accepted values of β depend to a certain extent on the solar cycle phase and solar wind conditions and can be assumed to be, on average, $\beta_0^{ce} = 4\times10^{-7}\ s^{-1}$ and $\beta_0^{ph} = 1.0\times10^{-7}\ s^{-1}$ for charge exchange (at the equator) and photoionization rates, respectively.

The 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 the region $R < 0.1$–0.2 a.u. (Holzer, 1977). In this paper, the electron impact ionization rate will not be considered at all. The solar photon input to ionization rate β_0 was assumed earlier to be due to the direct photoionization process of hydrogen atoms only

$$H+ph \rightarrow H^+ + e. \tag{1}$$

Here and further on, the letter "e" designates electron, "ph", photon, and "p", proton. However, to photoionize hydrogen atoms there exists another possibility, which we shall call the 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 photons and transfer not to the ground state but to the metastable H(2S) state. The atom can also be excited directly to a metastable state by collisions with solar wind plasma ions and electrons. While being in this metastable state, the hydrogen atom may be ionized by solar photons with a wavelength shorter than $\lambda_0 = 3646$ Å (which are rather abundant in the solar spectrum), as well as by collisions with solar wind plasma electrons and ions.

This way of photoionization has never, to my knowledge, been taken into account before, 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 the metastable state is calculated, then the possible fates of such metastable atoms are considered, and finally the ionization rate due to the indirect photoionization channel is determined.

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

Let us now consider the excitation of a hydrogen atom, which is in the ground H(1S) state, to the 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 a few kiloelectronvolts energy is rather low—the typical value for processes of such type is much less than 10^{-16} cm^2 (e.g. Bayfield, 1969). This value is much lower than the cross-section of resonance charge transfer for the same collision partners (2×10^{-15} cm^2), which is responsible for the major part of the ionization rate (β_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 collisions is less than 10^{-17} cm^2 (Callaway and McDowell, 1983). This value would correspond to an excitation rate less than 10^{-9} s^{-1} at Earth orbit, which is much lower than the value of direct ionization rate β_0 and will therefore be neglected. The solar radiation in Lyman series of hydrogen lines is absorbed with certain efficiency by hydrogen atoms, therefore hydrogen atoms can be excited to the states with the principal quantum numbers $n > 2$, which may decay, in their turn, to the H(2S) state with the emission of the photons

$$\mathrm{H(1S)+ph} \rightarrow \begin{cases} \mathrm{H(3P)} \rightarrow \mathrm{H(2S)+ph} \\ \mathrm{H(4P)} \rightarrow \mathrm{H(2S)+ph} \\ \cdots \end{cases} \quad (2)$$

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

The total intensity of the solar Ly-β ($\lambda = 1025.7$ Å) line is $E_\beta^0 = 6\times10^{-2}$ erg (cm^2 s)$^{-1}$ at Earth orbit (Timothy, 1977). To assess the linewidth, let us assume that the same atoms that emit in Ly-α ($\lambda = 1215.6$ Å), are responsible for the Ly-β emission. The linewidth is determined by the Doppler shifts due to the velocities of individual atoms and then the ratio $\kappa = \Delta\lambda/\lambda$ has to be constant for both lines. For Ly-α, the linewidth is well known—$\Delta\lambda = 0.8$ Å (e.g. Vidal-Madjar, 1977) and then $\kappa = 6.5\times10^{-4}$.

The radiation flux density in the line is

$$\rho_\omega(R) = \frac{1}{c}\left|\frac{\mathrm{d}E}{\mathrm{d}\omega}\right| = \frac{1}{c}\frac{E}{\kappa\omega}, \quad (3)$$

where ω is wave circular frequency, c is velocity of light, and $E(R) = E^0(R_0/R)^2$ is the intensity of the solar line.

The probability of photoexcitation of hydrogen atoms can be calculated exactly (e.g. Bethe and Salpeter, 1957). Taking into account that the probabilities of the H(3P) state subsequently making transitions to the H(1S) and H(2S) states are 0.882 and 0.118, respectively, one finally obtains the excitation rate to the H(2S) state at Earth orbit:

$$\beta_0^{2S} = 4\times10^{-7}\ \mathrm{s}^{-1}.$$

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

$$\beta^{2S}(R) = \beta_0^{2S}\left(\frac{R_0}{R}\right)^2. \quad (4)$$

A similar analysis for the solar Ly-γ line ($\lambda = 972.5$ Å) with energy flux $E_\gamma^0 = 1.5\times10^{-3}$ erg (cm^2 s)$^{-1}$ (Timothy, 1977) shows that the excitation rate of H(2S) through the H(4P) state is 3.2×10^{-9} s^{-1} at Earth orbit, which is much lower than that through the H(3P) state and can therefore be safely neglected as well as all the other radiation channels.

For the sake of completeness it should be noted that radiative recombination in the solar wind plasma may also produce hydrogen atoms in the metastable state. However, the process is not efficient, contributes only a minor fraction to the population of neutral atoms in interplanetary space (e.g. Holzer, 1977), and the majority of such atoms are in the ground state (e.g. Bethe and Salpeter, 1957). Moreover, hydrogen atoms, generated by recombination, belong to the population of neutrals with very specific kinematic characteristics—neutral solar wind—which is clearly distinct from atoms of interstellar origin and outgassed from interplanetary dust.

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

Let us consider now what may happen with the metastable hydrogen atom in interplanetary space. First of all, without any external interactions this atom will decay to the ground state by emission of two photons at a rate of $\delta^d = 8.226\ s^{-1}$ (Shapiro and Breit, 1959), i.e. with the lifetime $t_d = 0.12$ s. We shall denote corresponding rates for different H(2S) depopulation channels by the symbol δ^d with appropriate additional superscripts. Collisions with solar 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 may eventually decay to the ground or metastable state of the atom. Also, the decay of the metastable atom can be caused by the solar wind magnetic field. The major possible channels are the following

$$\mathrm{H(2S)} \rightarrow \mathrm{H(2S)} \rightarrow \mathrm{H(1S)} + \mathrm{ph} + \mathrm{ph} \quad \text{(a)}$$

$$\rightarrow \mathrm{H(2S)} + \mathrm{p, e, ph} \rightarrow \mathrm{H}(n > 2) + \cdots$$

$$\rightarrow \mathrm{H(1S)} + \mathrm{ph} \quad \text{(b)}$$

$$\rightarrow \mathrm{H(2S)} + \mathrm{ph} \quad \text{(c)}$$

$$\rightarrow \mathrm{H(2S)} + \mathrm{p, e} \rightarrow \mathrm{H(2P)} + \cdots$$

$$\rightarrow \mathrm{H(1S)} + \mathrm{ph} \quad \text{(d)}$$

$$\rightarrow \mathrm{H(2S)} + \mathrm{p, e, ph} \longrightarrow \mathrm{H}^+ + \cdots \quad \text{(e)}$$

$$\rightarrow \mathrm{H(2S)} + \text{magnetic field} \rightarrow \mathrm{H(1S)} + \cdots. \quad \text{(f)}$$

(5)

We note that channel (c) again leads to the hydrogen atom in the metastable state, and channel (e) corresponds to indirect ionization. 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.

3.1. *Collisions with solar wind ions and electrons*

The major effect of the collisions with solar wind protons and electrons is the transition from the $2S_{1/2}$ state to the $2P_{1/2}$ or $2P_{3/2}$ states which results in the subsequent very fast (1.6 ns) emission of Ly-α photons and hydrogen atoms in the ground $1S_{1/2}$ state. The solution for the problem of collisionally induced transitions to 2P states of hydrogen atoms was given by Purcell (1952).

The solar wind electron (proton) number density $n_e(n_p)$ is inversely proportional to the square of the distance from the Sun for $R > 0.05$ a.u. (Holzer, 1977), and equal to $n_e^0(n_p^0) = 5\ \mathrm{cm}^{-3}$ at Earth orbit. Also inversely proportional to the square of R are transition rates from H(2S) to H(2P) due to collisions with electrons $\delta^{d,e}(R)$ and protons $\delta^{d,p}(R)$. For assumed solar wind plasma density and $V_p = 400$ km s^{-1} and $T_e^0 = 10^4$ K one obtains $\delta_0^{d,e} = 2.9 \times 10^{-4}\ s^{-1}$ and $\delta_0^{d,p} = 3.5 \times 10^{-4}\ s^{-1}$.

Alpha particles constitute approx. 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 $\delta^{d,p}$.

It should be noted that the corresponding effective depopulation cross-section

$$\sigma^{d,p} = \delta_0^{d,p}/(n_0^p V_p) = 1.85 \times 10^{-12}\ \mathrm{cm}^2$$

is unusually large. Among other channels involving collisions with solar wind plasma particles, the largest cross-section characterizes the process of resonance charge exchange

$$\mathrm{H}^+ + \mathrm{H(2S)} \rightarrow \mathrm{H(2S)} + \mathrm{H}^+. \quad (6)$$

Though the cross-section for this process is rather high—$60 \times 10^{-16}\ \mathrm{cm}^2$ (Reinhold and Miraglia, 1987)—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*

The magnetic field B is frozen into the solar wind plasma and the metastable atom would feel the electric field

$$\mathbf{E} = \frac{1}{c}\mathbf{V} \times \mathbf{B}. \quad (7)$$

For the small electric fields, the H(2S) state lifetime t_E is determined by the expression (Bethe and Salpeter, 1957)

$$t_E = t_p(E/475)^{-2}, \quad (8)$$

where E is in units of volts per centimetre, and $t_p = 1.6 \times 10^{-9}$ s is the lifetime of the H(2P) state. The magnetic field decreases with increasing distance from the Sun, and at Earth orbit $B_0 < 10^{-4}$ G. Obviously the most pronounced effect would be in the region close to the Sun. The radial component of magnetic field depends on distance from the Sun roughly according to:

$$B^r(R) = B_0^r(R_0/R)^2. \quad (9)$$

At close approaches to the Sun, the magnetic field vector is almost parallel to the solar wind velocity vector V_{sw}, i.e. the radial component of the 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 in this case to R^4, is much longer than t_d and equals that for two photon decays only at $R = 0.03\ R_0$. One can therefore safely neglect the effect of the interplanetary magnetic field.

3.3. *Interaction with solar photons*

Interaction with solar photons may result either in photoionization (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.

First we consider the photoionization. The solar spectrum is assumed to be that of the blackbody with a temperature $T_s = 6000$ K. We also assume here 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

$$\delta^{i,ph}(R) = \delta_0^{i,ph}(R_0/R)^2 \qquad (10)$$

and

$$\delta_0^{i,ph} = \mu c \int_{\omega_0}^{\infty} \sigma(\omega)\, dN_\omega, \qquad (11)$$

where $\omega_0 = 5.16 \times 10^{15}\ s^{-1}$ is the threshold circular frequency for the photoionization, c is the velocity of light, $\mu = I_0/(4\sigma_{SB}T_s^4)$, $I_0 = 1.39 \times 10^6$ erg $(cm^2\ s)^{-1}$—solar constant (radiant flux density at 1 a.u.), σ_{SB} is the Stephan–Boltzmann constant, $\sigma(\omega)$ the photoionization cross-section, and dN_ω the photon number density distribution at temperature T_s.

For the 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. The blackbody approximation of the solar spectrum is therefore adequate for the purpose.

For the hydrogen atom, the photoionization cross-section can be calculated exactly (e.g. Frank-Kamenetsky, 1959). The value of μ is equal to 0.47×10^{-5} and one obtains $\delta_0^{i,ph} = 1.06\ s^{-1}$.

Let us now consider the excitation of the hydrogen atom from the metastable state H(2S). For the excitation to the H(3P) state, the photon wavelength is $\lambda = 6562.8$ Å (Balmer Hα line). The irradiance in Hα is a Fraunhofer line with a deep minimum down to 0.16 of the value of continuum (David, 1961; White, 1964), where solar irradiance is equal to 1.6×10^2 erg $(cm^2\ s\ Å)^{-1}$ (Arvesen *et al.*, 1969). Spectral radiation density responsible for the excitation of atoms depends then on the radial velocity of the atoms. For neutral hydrogen atoms originating from outgassing of interplanetary dust, the initial radial velocity is very small since dust particles are moving along almost circular orbits and the lifetime of atoms as neutrals is also small which does not allow the transformation of the initial velocity to the motion in radial direction. The spectral density for excitation would therefore correspond to the very minimum of the Fraunhofer line. For interstellar hydrogen the spectral density for excitation would be somewhat higher. For example, for a radial velocity of 20 km s^{-1}, the spectral density would be 0.25 of the level of continuum (White, 1964). We assume here that the effective solar spectral irradiance is 0.2 of the level of continuum. The H(3P) state with the probability 0.882 decays to the ground state and with probability 0.118 returns back to the H(2S) state. Therefore the depopulation rate by Balmer Hα photons is then

$$\delta_0^{d,ph,n=3} = 1.51\ s^{-1}.$$

For excitation to the H(4P) state, the photon wavelength is $\lambda = 4861.3$ Å (Balmer Hβ line). Solar irradiance at Balmer Hβ constitutes 0.13 of the continuum level (David, 1961; White, 1962), which is equal to 2.1×10^2 erg $(cm^2\ s\ Å)^{-1}$ (Arvesen *et al.*, 1969). We assume again that effective irradiance at the line is 0.2 of the continuum level. The transition probability for H(4P) to return to the H(2S) state is 0.12. Then the depopulation rate at Earth orbit is

$$\delta_0^{d,ph,n=4} = 0.19\ s^{-1}.$$

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 of H(2S) state by photoexcitation is

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

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.

4. PHOTOIONIZATION RATE

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

(i) hydrogen atoms are excited to the 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 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 the rate $\delta^{i,ph}(R)$.

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

$$\eta(R) = \beta_0^{2S}\left(\frac{R_0}{R}\right)^2 \frac{\delta_0^{i,ph}}{\delta^{d}\left(\frac{R}{R_0}\right)^2 + \delta_0^{d,ph} + \delta_0^{i,ph}}. \quad (12)$$

5. DISCUSSION

It is more convenient to consider the dependence on distance from the Sun not of the ionization rates but of those multiplied by $(R/R_0)^2$. For such values the dependences are constants if the ionization rates are inversely proportional to the square of the distance from the Sun, which is the case for ionization rates due to direct photoionization processes and charge exchange on solar wind ions.

The calculated dependence of $\eta^*(R) = \eta(R)(R/R_0)^2$ is shown in Fig. 1. Also shown are ionization rates corresponding to direct photoionization and charge exchange on solar wind protons. The ionization rate due to charge exchange is believed now to depend strongly on heliographic latitude, its value at the equator being twice as large as that at solar poles (e.g. Lallement, 1988).

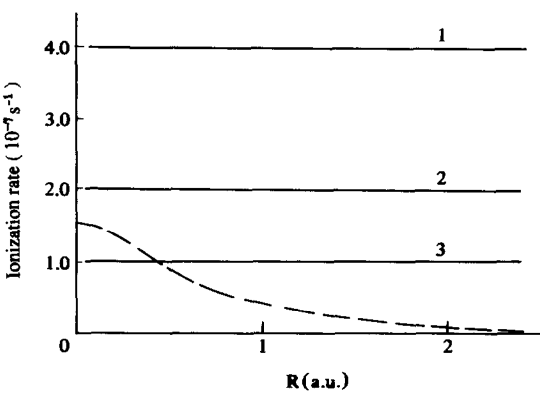

FIG. 1. REDUCED IONIZATION RATE DEPENDENCES ON DISTANCE FROM THE SUN R.
Dashed line: — — $\eta(R)$ $(R/R_0)^2$ indirect photoionization. Solid lines: (1) $\beta^{ce}(R)$ $(R/R_0)^2$ at equator; (2) $\beta^{ce}(R)$ $(R/R_0)^2$ at poles; (3) $\beta^{ph}(R)$ $(R/R_0)^2$ for direct photoionization.

At large distances from the Sun ($R > 1$–2 a.u.), the ionization rate through the 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 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% 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 the solar system, its influence on the neutral hydrogen atoms outgassing from interplanetary dust grains seems to be significant and must be taken into account.

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. Providing the interaction with magnetospheric/ionospheric ions and electrons, as well as electric/magnetic fields, does not affect the lifetime of the 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 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 1–2 a.u. from the Sun almost all metastable atoms decay through this channel. Taking into account that 12% of hydrogen atoms excited by solar radiation to the H(3P) state decay to the H(2S) metastable state, while 88% decay to the H(1S) state with the emission of Ly-β photons, one can expect that I_b would be roughly four times lower than the sky background radiation in the Ly-β line.

Background radiation in Ly-β constitutes about 2 R (Sandel *et al.*, 1978; Shemansky *et al.*, 1979) and hence $I_b = 0.5$ R (1 R $= 10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}). Two-photon decay is characterized by a rather broad spectrum of the emitted photons (Spitzer and Greenstein, 1951). For the range of maximum spectral density around $\lambda = 1500$ Å, one obtains photon flux 3×10^{-4} R Å^{-1} due to two-photon decay. This flux is approximately two orders of magnitude lower than that of measured e.u.v. background radiation (e.g. Paresce and Jakobsen, 1980).

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