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HYDROGEN ON VENUS: EXOSPHERIC DISTRIBUTION AND ESCAPE

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Abstract—Charge exchange between H and H^+ and momentum transfer between fast O and H provide comparable sources for suprathermal H atoms in Venus' exosphere. The fast O atoms are produced by dissociative recombination of O_2^+ . The spatial distribution of suprathermal H was calculated using an approximate numerical solution of the time-independent Boltzmann equation. Sources of suprathermal H atoms were specified on the basis of measurements by *Pioneer Venus*. Reactions involving H_2 were neglected in the absence of direct experimental information on the concentration of H_2 and on the grounds of indirect arguments suggesting its mixing ratio should be less than 0.5 ppmv. Computed densities of suprathermal H are in satisfactory agreement with profiles derived earlier from analysis of Lyman- α airglow by *Mariners* 5 and 10, and *Veneras* 11 and 12. The dayside emission at radial distances larger than 18,000 km is attributed to scattering of solar photons by fast H atoms produced primarily on the nightside near midnight. The nightside ionosphere, and consequently the source of suprathermal H, are expected to vary in response to changes in the solar wind. Observations of the variability of Lyman- α emission on the dayside could provide a useful test of the model, in particular its description of conditions in the nightside ionosphere and its neglect of fast H produced by reactions involving H_2 . Charge transfer of H with nightside H^+ accounts for approximately 70% of the hydrogen escaping from Venus. The total escape rate is estimated to be between 0.4 and 1×10^7 atoms $cm^{-2} s^{-1}$.

INTRODUCTION

The outer atmosphere of Venus contains significant quantities of atomic hydrogen, first detected with instrumentation on the United States spacecraft *Mariner 5* (Barth *et al.*, 1967). The spatial distribution of Lyman- α airglow was unexpectedly complex, with at least two components to the emission on the dayside, and with evidence for a large day-night asymmetry (Barth *et al.*, 1968; Wallace, 1969).

Early investigations focused on the nature of the dayside emission. The separate components exhibited scale heights which differed by about a factor of 2. McElroy and Hunten (1969) suggested that the more compact emission reflected scattering of solar radiation by D, while the outer component was attributed to H at a temperature of about 700 K, presumed to represent conditions near the base of Venus' exosphere. Barth (1968) argued that the component with the smaller scale height could indicate a source of emission due to exospheric H_2 . Neither suggestion has stood the test of time, however. The deuterium abundance of Venus' atmosphere is much less than required by McElroy and Hunten (McElroy and Hunten, 1969; Wallace *et al.*, 1971) and quantities of H_2 needed to perturb the

distribution H in the lower exosphere would provide unacceptably large fluxes of H to the outer exosphere (McElroy and Hunten, 1969).

The temperature of Venus' dayside exosphere is not 700 K, but closer to 350 K (Broadfoot *et al.*, 1974; Kumar and Hunten 1974; Kumar and Broadfoot, 1975; Niemann *et al.*, 1979a). The puzzle posed by the *Mariner 5* observations concerns thus not the nature of the inner component of the observed emission but rather the source of luminosity in the outer zone. Much of the recent work is concerned with analysis of the processes responsible for production and removal of the suprathermal atoms required to populate higher altitudes of Venus' dayside exosphere. Attention has focused for the most part on

and

where * denotes an atom with mean energy significantly higher than that of the average background neutral gas.

The kinetic energy of the proton is approximately conserved in reactions (1) and (2). As a consequence the velocity distribution of the product H atoms is expected to reflect the temperature of H^+ . The fast oxygen atoms

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in (3) are produced by recombination of O_2^+ ,

If one of the O atoms in (4) is formed in the 1D state, with the second in the 3P ground state (Zipf, 1970), then the average initial energy of O^* is 2.5 eV, corresponding to a mean speed of 5.5 km s^{-1} . Transfer of momentum in subsequent collisions with H, reaction (3), can provide a source of H^* with speeds as high as 13.7 km s^{-1} (assuming a mean thermal speed for H of 3 km s^{-1}). As we shall see, reaction (3) makes an important contribution to the distribution of H in the dayside exosphere. The importance of (1) and (2) in this context was raised earlier by Sze and McElroy (1975) and Chamberlain (1977) and has been investigated further by Penner (1977), Kumar *et al.* (1978), Cravens *et al.* (1980) and Hodges and Tinsley (1981, 1982).

The wealth of data from the *Pioneer Venus* mission allows us to remove many of the uncertainties present in these early studies. Concentrations of O and O^+ were found to be an order of magnitude larger than values predicted previously (Taylor *et al.*, 1979a,c, 1980; Niemann *et al.*, 1979a, b, 1980; Keating *et al.*, 1980). A large temperature asymmetry was observed between the day and nightside in the upper atmosphere, with temperatures of 300 K at noon and 100 K at midnight (Niemann *et al.*, 1979a, b, 1980; Keating *et al.*, 1980). Information was obtained also on the temperature and composition of both day and nightside ions (Taylor *et al.*, 1979a, b, c, 1980; Brace *et al.*, 1980; Miller *et al.*, 1980; Theis *et al.*, 1980). These data set the stage for more realistic modeling of the distribution of exospheric hydrogen.

We shall emphasize contributions to the suprathermal hydrogen budget from reactions (1)–(3). Ionospheric reactions involving H_2 could be important if the mixing ratio of H_2 at the turbopause were as large as 10^{-5} (Kumar and Hunten, 1974; Sze and McElroy, 1975). There is no direct evidence however for large concentrations of H_2 in Venus' upper atmosphere. Concentrations of H_2 as large as 10^{-5} would provide an unacceptably large source of thermospheric H (McElroy and Hunten, 1969) and would pose problems also for models of the nightside ionosphere (Cravens *et al.*, 1983). Consideration of photochemical processes in the stratosphere suggests an upper limit to the H_2 abundance of 5×10^{-7} (Yatteau, 1983); in this case reactions involving H_2 provide a negligible source of suprathermal H and are omitted in what follows.

The source of fast hydrogen atoms from reactions (1)–(3) is sufficient to account for the observed distribution of Venus' exospheric H. These reactions play a dominant role in regulating escape of hydrogen. An understanding of processes determining the

distribution of exospheric hydrogen is prerequisite to a more comprehensive study of the origin and evolution of Venus' H_2O . Models for contemporary exospheric H are an important step towards this objective.

Observational data for H are summarized in Section 2. The model used to calculate the distribution of suprathermal H is developed in Section 3. Source mechanisms are treated in Section 4. Relevant input data are discussed in Section 5 and results are given in Section 6. Reactions (1) and (3) are shown to provide the dominant sources of hydrogen in Venus' extended exosphere, and escape of H is regulated for the most part by (1). Principal conclusions of the study are given in Section 7.

2. OBSERVATIONS

Airglow at Lyman- α was observed on all spacecraft to Venus since *Mariner 5*. *Mariner 5* made measurements along tangent paths off both the bright and dark limbs and also detected emission from the altitude region between the spacecraft and dark disc (Barth *et al.*, 1967). Similar data were obtained by *Mariner 10* (Broadfoot *et al.*, 1974). The *Venera 9* and *10* spacecraft were placed in highly elliptic orbits and made about a dozen surveys of emissions from the bright disc and sunlit exosphere (Bertaux *et al.*, 1978). *Venera 11* and *12* flew by Venus obtaining data for the disk and exosphere on the nightside, with scans across the sunlit hemisphere including the exosphere near the South Pole (Bertaux *et al.*, 1981). Additional information is available from the u.v. spectrometer on *Pioneer Venus* (Stewart *et al.*, 1979).

Analysis of Lyman- α data generally proceeds as follows. Altitude profiles for the density of neutral species in a spherically symmetric exosphere are obtained using models such as those developed by Chamberlain (1963). The density distribution in these models is specified by three parameters: the density at the exobase, n_0 ; the exospheric temperature, T ; and the satellite critical level, R_{cs} . This last parameter denotes the upper limit to the altitude regime for which particles may be present in satellite orbits. Given an altitude profile for H, corresponding profiles for Lyman- α can be readily determined for specified geometries of observation. Model parameters are adjusted to obtain a satisfactory fit to the observed emission.

It was necessary in most cases to assume that the abundance of exospheric H included a combination of components at distinctly different temperatures. The component with the smaller scale height dominates close to the planet, and describes a population of H atoms in equilibrium with the temperature of the local

thermosphere. The component with the larger scale height was attributed to suprathermal atoms. The velocity distribution of atoms in the hot component may be expected to differ significantly from the idealization represented by Chamberlain's theory. This theory, with suitable choice of parameters, may be used, however, to provide a simple analytic fit to the observed distribution of suprathermal H. A more realistic model, as developed below, is required to elucidate the nature of the hot atom source.

Table 1 summarizes the parameters and applicable ranges of altitude for the different models proposed to describe hydrogen in Venus' exosphere. The models adopted by Wallace (1969) and Anderson (1976) (dark disc) allowed for the presence of particles in satellite orbits. The exobase was set at a planetocentric radius, r_{ex} of 6305 km, representing an altitude of about 250 km. Dayside concentrations of H derived from different sets of observations are in reasonably good agreement. Exobase densities for the thermal, or equilibrium, component generally lie between 1 and $3 \times 10^5 \text{ cm}^{-3}$, with temperatures close to 300 K. Results from *Venera*

11 and 12 (Bertaux *et al.*, 1982), however, suggest densities lower than this by a factor of between 2 and 4. The *Venera* observations were made at a much higher latitude and could reflect a possible latitudinal variation in thermospheric H. Wallace (1969), as pointed out by Anderson (1976), used an incorrect temperature dependence for the H absorption coefficient; this error is important in the optically thick region dominated by the thermal component but should not affect his calculations for the hot component. Wallace's results should be valid at radial distances larger than 10,000 km; densities for his model given in Table 1 were scaled by a factor of 0.725, as suggested by Anderson. Bertaux *et al.* (1978) were able to fit their dayside observations with a single temperature; their measurements are consistent however with the presence of two distinct components. Concentrations derived by Takacs *et al.* (1980) for the hot component observed by *Mariner* 10 are somewhat lower than the earlier values, reflecting perhaps quieter solar conditions at the time of the *Mariner* 10 encounter.

TABLE 1. EXOSPHERIC MODELS FOR HYDROGEN ON VENUS

Observations	$T(\text{K})$	$n_0 (\text{cm}^{-3})$	Solar zenith angle	Radial distance (10^3 km)
<i>Mariner</i> 5				
Wallace (1969)				
(Model 4)				
Bright Limb				
Cold	325	1.1×10^5	30°	6–9
Hot	1020	8.4×10^2	30°	6–9
Dark Limb				
Hot	1020	8.4×10^2	150°	9–30
Anderson (1976)				
Bright Limb				
Cold	275 ± 50	$2 \pm 1 \times 10^5$	30°	6–9
Hot	1020 ± 100	1.3×10^3	30°	9–30
Dark Disk				
Cold	150 ± 50	$2 \pm 1 \times 10^5$	$135\text{--}90^\circ$	6–9
Hot	1500 ± 200	10^3	$135\text{--}90^\circ$	9–13
<i>Mariner</i> 10				
Takacs <i>et al.</i> (1980)				
Bright Limb				
Cold	275 ± 50	1.5×10^5	18°	6–9
Hot	1250 ± 100	500 ± 100	$18\text{--}60^\circ$	9–30
Dark Limb				
Cold	150 ± 25	$1.0 \pm 0.5 \times 10^5$	$90\text{--}120^\circ$	6–9
Hot	800 ± 200	$2.0 \pm 0.5 \times 10^3$	144°	9–30
<i>Venera</i> 9–10				
Bertaux <i>et al.</i> (1978)				
Bright Limb	500 ± 100	1.5×10^4	50°	6–11
<i>Venera</i> 11–12				
Bertaux <i>et al.</i> (1982)				
Bright Limb				
Cold	300 ± 25	$4 \pm \frac{3}{2} \times 10^4$	80°	6–9
Hot	1000	10^3	90°	9–30

The picture for the nightside is more complicated. Wallace (1969) found no evidence for a thermal component off the dark limb. Anderson (1976) suggested that the lack of an observable thermal component in this region might be attributed to absorption of Lyman- α by a cold dense atmosphere near the dark limb. His analysis of the *Mariner 5* dark disk data indicated an exobase density of $2 \times 10^5 \text{ cm}^{-3}$ at a temperature of 150 K, in agreement with later calculations by Takacs *et al.* (1980) for *Mariner 10*. Wallace's model for the suprathermal component at large planetocentric distances on the nightside indicated densities similar to values on the dayside. Anderson's analysis of the dark disk data for r less than 13,000 km suggested that the density of nightside suprathermal H might increase with approach to the terminator and a similar conclusion was drawn by Takacs *et al.* (1980) from analysis of the *Mariner 10* data at solar zenith angles between 90° (morning terminator) and 144° .

The interpretation of Lyman- α observations on the nightside is particularly difficult and inferences regarding the concentration of H are correspondingly uncertain. Data from *Pioneer Venus* reveal a bulge in hydrogen on the nightside with densities near the critical level at dawn 100 times larger than values observed during the day. Models for the *Mariner 5* and 10 results do not allow for this complication. High concentrations of H on the nightside could account, through backscatter, for the large emission rates of Lyman- α observed by *Mariner 5* across the dark disc (see Takacs *et al.*, 1980).

In summary, the exospheric temperature of Venus ranges from about 300 K on the dayside to 110 K at night (Keating *et al.*, 1980; Niemann *et al.*, 1980). The concentration of thermal H at the critical level is about 10^5 cm^{-3} during the day, increasing after sunset to values near 10^7 cm^{-3} at about 0400. The density of H at all locations reflects a combination of thermal and suprathermal atoms. The density of suprathermal atoms at low altitude appears to increase from the subsolar point towards the terminator. Densities of suprathermal H derived from *Mariner 5* show little variability at high altitude. Concentrations from *Mariner 10* however suggest higher values at high altitude on the dayside.

We shall attempt in what follows to account for the profiles presented above on the basis of source rates for suprathermal H calculated for reactions (1)–(3). The dayside results provide an excellent standard of comparison. Geometrical and other interpretational complexities make comparison of present results with nightside data necessarily tentative, but none the less valuable.

3. MATHEMATICAL FORMULATION

Possible trajectories for hydrogen atoms reaching a point $\bar{r}_1$ in the exosphere are shown in Fig. 1a. The trajectory labeled 1 denotes the contribution at $\bar{r}_1$ from a source at $\bar{r}_0$ well above the exobase, so that H atoms undergo no collisions between $\bar{r}_0$ and $\bar{r}_1$. Trajectory 2 represents contributions from hot H atoms emerging from the collision-dominated region below the exobase. Particles travelling through the exosphere may fall back to the planet and be reflected by the lower atmosphere, reaching $\bar{r}_1$ along trajectory 3.

We seek an expression for the density in phase space at $\bar{r}_1$ of suprathermal H, $f(\bar{r}_1, \bar{v}_1)$, such that the total density at $\bar{r}_1$ is given by

$$n_{\text{H}^*}(\bar{r}_1) = \int d^3\bar{v}_1 f(\bar{r}_1, \bar{v}_1). \quad (5)$$

The geometry is illustrated in Fig. 1b. The velocity vector at $\bar{r}_1$ is specified by three coordinates: the speed v_1 ; the angle between the velocity and the radius vector, α_1 ; and the azimuthal angle, β_1 .

A particular choice of $\bar{r}_1$ and $\bar{v}_1$ specifies a unique orbit for atoms passing through $\bar{r}_1$ with velocity $\bar{v}_1$. For steady state conditions, the density of atoms in phase space along this orbit obeys the collisionless, time-independent Boltzmann equation

$$\bar{v} \cdot \bar{\nabla}_{\bar{r}} f(\bar{r}, \bar{v}) + \bar{a} \cdot \bar{\nabla}_{\bar{v}} f(\bar{r}, \bar{v}) = P_T(\bar{r}, \bar{v}), \quad (6)$$

where $\bar{a}$ defines the acceleration. The function $P_T(\bar{r}, \bar{v})$ ($\text{cm}^{-6} \text{ ster}^{-1} \text{ s}^2$) is specified such that $P_T(\bar{r}, \bar{v}) d^3\bar{r} d^3\bar{v}$ denotes the total number of hot H atoms produced per second in a volume $d^3\bar{r}$ around $\bar{r}$, with velocities in $d^3\bar{v}$ around $\bar{v}$. For a particular orbit, both $\bar{v}$ and $\bar{a}$ are functions of position along the orbit $\bar{r}$. We have

$$\bar{a}(\bar{r}) = -\frac{GM}{r^2} \frac{\bar{r}}{|\bar{r}|} \quad (7)$$

FIG. 1a. CONTRIBUTIONS TO THE HOT HYDROGEN CORONA. Trajectory 1 denotes atoms produced at r_0 above the exobase, and travelling to r_1 without collision. Trajectory 2 represents atoms produced below the exobase, reaching r_1 after collisions. Atoms produced above the exobase and reflected by the lower atmosphere are included in Trajectory 3.

FIG. 1b. ORBITAL PARAMETERS FOR ATOMS ABOVE THE EXOBASE. The contribution to the density at r_1 from atoms travelling along this orbit is obtained by integrating the production along the path denoted by the thick solid line. The level r_0 denotes the bottom of the collision-free region; s represents the path length along the orbit. Angular distances from perihelion are denoted by θ_0 and θ_1 . The velocity v_1 at r_1 has an angle α_1 with the local vertical, and the azimuthal angle is β_1 .

and $\bar{v}$ can be obtained from the inclination of the orbit with respect to the planet, from conservation of energy,

$$E = \frac{1}{2}m_H v^2 - \frac{GMm_H}{r}, \quad (8)$$

and angular moments,

$$L = m_H v r \sin \alpha. \quad (9)$$

The orbital equation is given by (Corben and Stehle, 1960)

$$\frac{1}{r} = A(1 + B \cos \theta), \quad (10)$$

where

$$A = \frac{GMm_H^2}{L^2},$$

$$B = (1 + 2EL^2/G^2M^2m_H^3)^{1/2},$$

M is the mass of the planet, m_H is the mass of a hydrogen atom, and G represents the gravitational constant. The angle θ denotes the planetocentric angular distance from perihelion, measured in the plane of the orbit.

Equation (6) can be simplified if all variables are expressed in terms of a parameter (s), the path length along the orbit. The speed of an atom travelling along the orbit is given by $v = ds/dt$ and

$$v \frac{df}{ds} = \frac{ds}{dt} \left(\bar{\nabla}_{\bar{r}} f \cdot \frac{d\bar{r}}{ds} + \bar{\nabla}_{\bar{v}} f \cdot \frac{d\bar{v}}{ds} \right) \quad (11)$$

$$= \bar{v} \cdot \bar{\nabla}_{\bar{r}} f + \bar{a} \cdot \bar{\nabla}_{\bar{v}} f.$$

Equation (6) may then be recast in the form

$$v \frac{df(s, \bar{v}(s))}{ds} = P_T(\bar{r}(s), \bar{v}(s)). \quad (12)$$

We integrate (16) along the orbit with boundary condition $f_0 = f(\bar{r}_0, \bar{v}_0)$ at $\bar{r}_0$ where the trajectory intersects the boundary of the collision-free region. Here f_0 represents the phase space density of atoms emanating from the collision-dominated region at lower altitudes. Using $ds = |\mu| |d\bar{r}|$, where $\mu = \cos \alpha$, we find

$$f(\bar{r}_1, \bar{v}_1) = \int_{|\bar{r}_0|}^{|\bar{r}_1|} d\bar{r} \frac{P_T[\bar{r}, \bar{v}(\bar{v}_1, \bar{r}_1, \bar{r})]}{v(\bar{v}_1, \bar{r}_1, \bar{r}) |\mu(\bar{v}_1, \bar{r}_1, \bar{r})|} + f[\bar{r}_0, \bar{v}_0(\bar{v}_1, \bar{r}_1, \bar{r}_0)], \quad (13)$$

where $\bar{v}$ and μ are functions of $\bar{v}_1$, $\bar{r}_1$, and $\bar{r}$ through equations (8) and (9).

Substituting (13) in (5) yields

$$n_H(\bar{r}_1) = \int v_1^2 dv_1 d\mu_1 d\beta_1 \int_{r_0}^{r_T} d\bar{r} \frac{P_T(\bar{r}, \bar{v})}{v|\mu|} + \int v_1^2 dv_1 d\mu_1 d\beta_1 f(\bar{r}_0, \bar{v}_0). \quad (14)$$

The radial integration is carried out to a distance r_T , representing the top boundary of the source region. The calculations assume a value of 6852 km for r_T . Limits of integrations for v_1 and μ_1 are obtained from equations (8–9). Since $r < r_1$, v_1 ranges from 0 to ∞ . For $r_1 v_1 < rv$, μ_1 ranges from -1 to 1 . If $r_1 v_1 > rv$, μ_1 ranges from $-\cos(\pi - \sin^{-1}(rv/r_1 v_1))$ to $\cos(\pi - \sin^{-1}(rv/r_1 v_1))$, and from $\cos(\sin^{-1}(rv/r_1 v_1))$ to 1 . The limits for β , the azimuthal angle, are 0 to 2π .

Our analysis assumes that the physical parameters of Venus' atmosphere depend only on solar zenith angle. The integration over β is simplified by restricting calculations to points along the planet–Sun line (noon and midnight), and to locations directly above the terminator. For a particular trajectory, the solar zenith angle corresponding to a radial distance r is obtained then from the orbit equation (10). The mathematical formulation presented here can be easily extended to more complicated geometries.

The first term in (14) results from production of particles above the exobase, and contains a removable singularity, at $\mu = 0$, arising from the change of variables from s to r . We use the change of variables suggested by Penner (1977) to remove this singularity. The second term in (14) represents the contribution to n_H from H atoms which have undergone collisions and requires therefore an evaluation of $f(\bar{r}_0, \bar{v}_0)$, the phase space density at the exobase.

Thermal velocities for atmospheric oxygen near the exobase are approximately 0.7 km s^{-1} on the dayside, 0.4 km s^{-1} at night. Hot H atoms reaching the region of interest (above 8000 km) are produced with average velocities of about 7 km s^{-1} . The kinematics of the hot H collisions may be simplified by assuming that the

background gas is at rest and that the hot H atoms travel in straight lines in a plane-parallel, collision-dominated region. The problem is then analogous to the description of photoelectron transport in the Earth's atmosphere and may be treated using the method described by Prather *et al.* (1978). Details are given in the Appendix.

We consider two sources of hot H at the exobase: atoms which originate below, and atoms which are produced above and subsequently reflected by the lower atmosphere. The flux of hot H atoms in the first component is calculated using the transport program with boundary conditions

$$I(-\mu, E, r_0) = I(+\mu, E, r_0), \quad E < E_{\text{esc}}, \mu > 0, \quad (15)$$

$$I(-\mu, E, r_0) = 0, \quad E \geq E_{\text{esc}}, \mu > 0,$$

where $I(\mu, E, r_0)$ ($\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1} \text{ster}^{-1}$) is analogous to the specific intensity in radiative transfer theory, and where E_{esc} is the escape energy for H (0.55 eV). These boundary conditions assume that all gravitationally bound particles emerging from the exobase fall back to the same region.

The transport formulation may also be used to calculate the source of atoms reflected by the lower atmosphere. Equation (A.5) implies that a hydrogen atom loses 11% of its original energy on average in a collision with O. We expect thus that a significant fraction of hot H will be reflected back to the exosphere. Monte-Carlo calculations by Chamberlain and Smith (1971) suggest that about 30% of the particles in the escaping tail of a Maxwellian distribution are reflected with speeds above the escape velocity. Hodges and Tinsley (1981) assumed that 30% of H atoms at any velocity are reflected with no change in energy. Our transport program allows us to calculate the energy distribution of reflected particles for any given incident flux. This is implemented by setting the source function equal to zero, adopting the upper boundary condition

$$\begin{aligned} I(-\mu, E, r_0) &= I(+\mu, E, r_0) + I_0(-\mu, E, r_0), \\ E &< E_{\text{esc}}, \mu > 0, \\ I(-\mu, E, r_0) &= I_0(-\mu, E, r_0), \\ E &\geq E_{\text{esc}}, \mu > 0, \end{aligned} \quad (16)$$

where $I_0(\mu, E, r_0)$ is the specific intensity of the incident particle stream. The presence of the term $I(+\mu, E, r_0)$ in (16) allows account to be taken of multiple reflections, a necessary feature since fast atoms are expected to bounce off the lower atmosphere several times before eventual thermalization. The incident intensity $I_0(-\mu, E, r_0)$ is obtained by integrating the production function P_T along the trajectory of particles

which intersect the level r_0 with energy E and $\mu = \cos^{-1}(\alpha)$.

The phase space density is easily derived from $I(\mu, E, r_0)$:

$$f(\bar{r}_0, \bar{v}_0) = f(\bar{r}_0, v_0, \mu_0) = I'(\mu_0, v_0, \bar{r}_0)/v_0 \quad (17)$$

where $I'(\mu_0, v_0, r_0)$ is defined such that

$$I'(\mu_0, v_0, \bar{r}_0) v_0^2 dv_0 = I(\mu_0, E_0, \bar{r}_0) dE_0 \quad (18)$$

for $E_0 = m_H v_0^2/2$.

Hodges and Tinsley (1981), in their Monte-Carlo calculations, included a number of additional processes which might affect the density distribution of H: ionization and removal of hot atoms above the exobase, photon scattering, and formation of satellite particles. These would not appreciably affect the densities calculated here.

Hot H atoms may be removed above the exobase by photoionization, by charge exchange with solar wind or ionosheath protons, and by ionization due to collisions with ionosheath electrons. The ionization rate is estimated at $1.7 \times 10^{-6} \text{s}^{-1}$ for the ionosheath, at $1 \times 10^{-6} \text{s}^{-1}$ for the region above the bow shock. With orbital periods of order 10^3 – 10^4 s, the loss probability per orbit is no greater than 0.02.

The momentum of a hydrogen atom may be perturbed by scattering of solar Lyman- α radiation which results in a change of momentum in the antisunward direction of

$$\Delta p = \frac{h}{\lambda_\alpha} = 5.45 \times 10^{-22} \text{ g cm} \quad (19)$$

where h is Planck's constant, and λ_α is the wavelength of Lyman- α radiation. The emission rate factor g , defined as the number of photons scattered per second per atom, had a value of $4.1 \times 10^{-3} \text{s}^{-1}$ at the time of the *Mariner 5* flyby (Anderson, 1976). The force due to radiation pressure would then be

$$F_{\text{rad}} = (\Delta p)(g) = 2.23 \times 10^{-24} \text{ dyn}. \quad (20)$$

For comparison, the gravitational force on a hydrogen atom at the surface of the planet is $1.47 \times 10^{-21} \text{ dyn}$. Radiation pressure becomes a noticeable perturbation to gravity only at altitudes above 8 Venus radii (48,000 km). The effect of radiation pressure is consequently small in the altitude range of interest here.

Collisions in the exosphere are rare, and H atoms on satellite orbits travel several times around the planet before falling into the lower atmosphere. Calculations by Hodges and Tinsley (1981) showed that only 1% of exospheric hydrogen atoms in Venus are in satellite orbits. These atoms are removed efficiently by collisions with neutral atmospheric constituents and

with thermal hydrogen atoms in the nightside bulge region. Their contribution is consequently omitted in what follows.

4. PRODUCTION OF SUPRATHERMAL H

The source function for suprathermal H may be written in the form

$$P_T(\bar{r}, \bar{v}) = P_{H^+-H}(\bar{r}, \bar{v}) + P_{O^*-H}(\bar{r}, \bar{v}) \quad (21)$$

where $P_{H^+-H}(\bar{r}, \bar{v})$ and $P_{O^*-H}(\bar{r}, \bar{v})$ denotes rates for production by reactions (1) and (3) respectively. We omit production due to reaction (2), charge transfer of H^+ with O; the scale height of O is small compared to that of H in regions of the nightside where H^+ densities and temperatures are high, ensuring a negligible role for (2) compared to (1). We omit also reactions involving H_2 ; as noted earlier there is no evidence for H_2 or H_2^+ in Venus' thermosphere (Hartle and Taylor, 1983). Photochemical considerations suggest an upper limit to the mixing ratio of H_2 at the turbopause of 5×10^{-7} (Yatteau, 1983). Reactions involving H_2 are important for H^* only when the mixing ratio of H_2 exceeds 10^{-6} (Sze and McElroy, 1975; Kumar *et al.*, 1981). Production of H^* due to charge transfer between atmospheric gases and protons in the solar wind may also be ignored; product H^* in this case is too fast to contribute to the observed corona.

The function $P_{H^+-H}(\bar{r}, \bar{v})$ may be easily derived if we assume that the velocity of the original H^+ ion is conserved in the charge transfer process,

$$P_{H^+-H}(\bar{r}, \bar{v}) = \left[\left(\frac{m_H}{2\pi k T_i} \right)^{3/2} \times v^2 e^{-(m_H v^2 / 2k T_i)} \right] [K_{H^+-H} n_{H^+}(\bar{r}) n_H(\bar{r})], \quad (22)$$

where the reaction rate constant K_{H^+-H} is given by (Banks and Kockarts, 1973)

$$K_{H^+-H} = \sigma_{H^+-H} \left[\frac{8k}{\pi m_H} (T_n + T_i) \right]^{1/2}. \quad (23)$$

Here m_H denotes the mass of a hydrogen atom; T_i and T_n are the temperatures of ions and neutrals, respectively; n_{H^+} and n_H represent the densities of H^+ and H at $\bar{r}$; and k is Boltzmann's constant. We adopted a value of $6 \times 10^{-15} \text{ cm}^2$ for the charge exchange cross section σ_{H^+-H} (Horwitz and Banks, 1973; Belyaev, Brezhnev and Erastov, 1967).

The Maxwellian distribution function is isotropic, and therefore the production function in (23) depends only on speed v . Production of H^* due to collisions of H

with energetic O is given by

$$P_{O^*-H}(\bar{r}, \bar{v}) d^3\bar{v} = \int_0^{E_{\max}} \sigma_{O^*-H} \times |\bar{v} - \bar{v}_0| I_0(E, \bar{r}) P(\bar{v}_0, \bar{v}) n_H(\bar{r}) dE. \quad (24)$$

Here, $I_0(E, \bar{r})$ is the specific intensity of O^* with energy E at $\bar{r}$, calculated using the transport formulation presented in the Appendix; $\bar{v}_0$ is the velocity of O^* at energy E ; and $E_{\max}$ is the maximum energy for O^* produced in (4), 2.5 eV. A value of $2.5 \times 10^{-15} \text{ cm}^2$ was adopted for the σ_{O^*-H} , the cross-section describing elastic scattering of O^* by H (Wofsy *et al.*, 1971). This choice is similar to the result obtained by Cooper *et al.* (1984) if we omit the forward peak in their differential scattering cross-section.

The function $P(\bar{v}_0, \bar{v})$ denotes the probability that H^* will emerge with velocity $\bar{v}$ after collision with O^* at velocity $\bar{v}_0$. The thermal velocity of H at 300 K, about 3 km s^{-1} , is comparable to the maximum speed for O^* , 5.5 km s^{-1} , and we must allow therefore for the initial velocity distribution of H. The final velocity, $\bar{v}$, is a function of the velocity of O^* , $\bar{v}_0$, the initial speed of the H atom, v^0 , the angle between $\bar{v}_0$ and $\bar{v}^0$, and the zenith and azimuthal angles for scattering in the center of mass system, θ_0 and ϕ_0 .

We calculated the probability function for fixed $\bar{v}_0$ by generating random values for each of the collision parameters. The distributions of v^0 and α were obtained from the Maxwell distribution, while θ_0 and ϕ_0 were generated using the differential scattering cross-sections. Our calculations assumed isotropic scattering in the center-of-mass system: modification of the procedure to allow for the differential cross-sections calculated by Cooper *et al.* (1984) would be straightforward but are considered unnecessary here in light of other inherent uncertainties in the overall treatment of H^* . The distribution of initial velocities for O^* , $\bar{v}_0$, is approximately isotropic. Thus the production function $P_{O^*-H}(\bar{r}, \bar{v})$ depends only on speed, as was the case for the charge exchange process (1).

The production function was assumed constant for computational convenience over intervals of initial speed of width 0.2 km s^{-1} . The average rate for production in a typical velocity bin ($\text{cm}^{-3} \text{ s}^{-1} \text{ ster}^{-1} \text{ bin}^{-1}$) is given by $P_{O^*-H}(\bar{r}, \bar{v})$ which may be related to $P_{O^*-H}(\bar{r}, \bar{v})$ by

$$P_{O^*-H}(\bar{r}, \bar{v}) = P_{O^*-H} v^2 \Delta v, \quad (25)$$

where Δv is the bin width, 0.2 km s^{-1} . Typical results for $P_{O^*-H}(\bar{r}, \bar{v})$ are illustrated for the dayside exobase in Fig. 2a. The computations were normalized to a density of thermal H of 1 cm^{-3} at a temperature of 300 K. The intensity of O^* at the dayside exobase was calculated

FIG. 2a. PRODUCTION OF HOT H BY COLLISIONS OF HOT O WITH THERMAL H ON THE DAYSIDE.

The production function ($\text{cm}^{-3} \text{s}^{-1} \text{ster}^{-1} \text{bin}^{-1}$) is denoted by the thick solid line. The hot O flux was calculated from the ionosphere of Theis *et al.* (1980) and scaled to a primary flux of $1 \text{ cm}^{-2} \text{s}^{-1} \text{eV}^{-1} \text{ster}^{-1}$. We used a thermal hydrogen density of 1 cm^{-3} at 300 K and a bin size of 0.2 km s^{-1} . The Maxwellian distributions of H^* associated with charge exchange of H with H^+ at 1000 and 2000 K are also shown and have been normalized to the same total production as the hot O process.

using the ionospheric profile measured by Theis *et al.* (1980). This intensity was then normalized to a value of $1 \text{ cm}^{-2} \text{s}^{-1} \text{ster}^{-1} \text{eV}^{-1}$ at the source energy, 2.5 eV. Figure 2b shows the corresponding production function with similar normalization for the nightside exobase. The nightside results were obtained using intensities of O^* calculated from the ionospheric profile of Taylor *et al.* (1980), orbit 65, with a thermal hydrogen temperature of 110 K. We also show for comparison in Figs. 2a and 2b production functions for reaction (1) with a variety of values for the temperature of H^+ . These results are scaled to provide a velocity integrated source equivalent to that for reaction (3). Hydrogen atoms with velocities greater than 10.2 km s^{-1} are able to escape from Venus. Note that the results at higher velocities, obtained for (3) on the dayside, mimic those for (1), with ion temperatures of about 1000 K. Temperatures of H^+ in the exosphere range from 2000

FIG. 2b. PRODUCTION OF HOT H ($\text{cm}^{-3} \text{s}^{-1} \text{ster}^{-1} \text{bin}^{-1}$) BY COLLISIONS OF HOT O WITH THERMAL H ON THE NIGHTSIDE. The calculation is the same as in Fig. 2a, but uses the ionospheric profile of Taylor *et al.* (1980) for orbit 65 and a neutral temperature of 100 K. The normalized Maxwellian production at 1000 K is also shown.

to 5000 K. It is clear therefore, from Figs. 2a and 2b, that reaction (1) may play a role in hydrogen escape proportionally larger than its contribution to the gravitationally bound suprathermal corona.

5. ATMOSPHERIC MODEL

We need models for the background neutral and ionized atmospheres in order to calculate the source and distribution of suprathermal H. Specifically we need the distribution of thermal exospheric H, the abundance of thermospheric and exospheric O and CO_2 , profiles for H^+ and O_2^+ and temperatures for neutrals and H^+ . We require this information for both day and nightsides of the planet. *Pioneer Venus* provides the first opportunity to formulate a realistic global model.

The Orbiter Neutral Mass Spectrometer (ONMS) experiment yields data for the concentration of atmospheric constituents above 150 km (Niemann *et al.*, 1979a, b, 1980) while the Orbiter Atmospheric Drag (OAD) experiment gives information on variations in

total density over a similar height range (Keating *et al.*, 1980). Densities from OAD are about 60% higher than those from ONMS. Hedin *et al.* (1983), in a recent analysis, scaled results from ONMS to agree with data from OAD. Their model is adopted for present purposes.

The exobase is usually defined as the level from which a fraction $1/e$ of fast particles moving straight up would escape without further collisions (Chamberlain, 1963). In terms of the collisional depth defined in equation (A.2) of the Appendix, it would be characterized by

$$\tau_{\text{ex}} = \sigma n_{\text{ex}} H_{\text{ex}} = 1, \quad (26)$$

where σ is the collision cross-section, n_{ex} denotes the density of neutral constituents at the exobase, and H_{ex} is the local scale height. The location of the exobase on Venus is determined mainly by atomic oxygen. The OAD results imply that the exobase is at an altitude of about 190 km at noon, dropping to 150 km at midnight. This conclusion assumes an average collision cross-section of about $3 \times 10^{-15} \text{ cm}^2$. We distinguish for present purposes two regions of the upper atmosphere, a collision-free environment where $\tau \leq 0.05$, and a lower altitude regime where collisions are important. The boundary is at about 300 km on the dayside, at about 170 km at night.

Concentrations of H were not measured directly by any of the in-situ experiments on *Pioneer Venus*. Information from observations of Lyman- α during earlier missions was summarized in Table 1. An independent determination of the densities near the exobase region has been presented by Brinton *et al.* (1979, 1980). They used densities of H^+ and O^+ from the Orbiter Ion Mass Spectrometer (OIMS) experiment, combined with densities of O and CO_2 from ONMS, to obtain densities of H, assuming a local equilibrium maintained by

In this case

$$n(\text{H}) = \frac{n(\text{H}^+)}{n(\text{O}^+)} [K_1 n(\text{O}) (T_i/T_g)^{1/2} + K_2 n(\text{CO}_2)] \quad (28)$$

where T_i denotes the ion temperature, T_g is the neutral temperature and K_1 and K_2 are constants appropriate for reactions (27).

The density of atomic hydrogen as a function of local time at 150 km is illustrated in Fig. 3. We used the smooth profile obtained by Mayr *et al.* (1980) based on the first three spherical harmonics in the spectral decomposition of the data presented by Brinton *et al.* (1979). The H density is fairly constant over the dayside,

FIG. 3. ATOMIC HYDROGEN DENSITIES AT 150 km AS A FUNCTION OF LOCAL TIME.

We have used the spectral decomposition (Mayr *et al.*, 1980) of the data of Brinton *et al.* (1979). Densities are scaled to a noontime value of $5 \times 10^4 \text{ cm}^{-3}$ (Brinton *et al.*, 1980).

with a value of about $5 \times 10^4 \text{ cm}^{-3}$, increasing rapidly at the terminator, exhibiting a nightside bulge with a maximum at about 0300. The enhanced nighttime density was not apparent in the analysis of Lyman- α data summarized in Table 1. As noted earlier, its absence reflects most probably difficulties in modeling the emission of Lyman- α from low altitudes on the nightside.

There are discrepancies also on the dayside. Results from the Lyman- α experiments on *Mariners 5* and 10 yield hydrogen densities between 1.4 and $4.2 \times 10^5 \text{ cm}^{-3}$ at 150 km on the dayside, in contrast to values of about $5 \times 10^4 \text{ cm}^{-3}$ derived using equation (28). The quality and ease of analysis of the optical data is superior on the dayside, and it is harder to resolve the discrepancy in this case. The H densities of Brinton *et al.* can be brought into closer agreement with the *Mariner* results if we make two plausible corrections: use of the OAD results for $n(\text{O})$ and $n(\text{CO}_2)$ in equation (28) results in an increase of 60% in the density of H; a recent

revision in the rate constant for (27b) (Brinton *et al.*, 1980) provides for a further 20% enhancement. These corrections lead to a revised dayside H density of $1 \times 10^5 \text{ cm}^{-3}$ at 150 km, in better agreement with the *Mariner* value. We may note also the value $5 \times 10^4 \text{ cm}^{-3}$, obtained by Bertaux *et al.* (1982) from *Venera* 11 and 12 measurements at the time of *Pioneer Venus*. It is possible that atmospheric conditions during the *Pioneer Venus* mission were different from those during the *Mariner* 5 and 10 encounters. Bertaux's measurements, however, were obtained in the polar region, while the results of Brinton *et al.* are restricted to the vicinity of the Equator. We believe that the results in Fig. 3 should be reliable to better than a factor of 2.

Our calculations adopt the profile in Fig. 3, scaled to a specific density at the subsolar point. This density will be used as an adjustable parameter to obtain an optimal fit to the observed distribution of exospheric H. Since the Brinton profile is based on data for the equatorial region, assumptions need to be made concerning the behavior of H at other latitudes. We assume that H is constant with latitude at 150 km on the dayside. The dark hemisphere is divided into three annular regions corresponding to solar zenith angles between 90° and 120° , 120° and 150° , and 150° and 180° . The pre-dawn bulge is assumed to occupy one sixth of each annulus, and an average H profile is calculated for each region. The procedure is illustrated in Fig. 4.

A hot hydrogen atom loses about half of its energy in

FIG. 4. ATOMIC HYDROGEN DENSITIES FOR THE NIGHTSIDE OF VENUS.

The numbers shown are average densities at 170 km in each region, and are taken from the profile of Fig. 3, scaling to a noon density of $1 \times 10^5 \text{ cm}^{-3}$ at 250 km (Anderson, 1976). The high densities near dawn are applied to only 1/6 of the annular areas, denoted by the pie-shaped cut.

collision with atmospheric H; the atom is thus effectively removed from the exospheric hot H flux after only one collision with thermal H. We correct for this effect, assuming that H in the region of the nightside bulge acts as an absorbing layer attenuating the source of H^* from below the collision free region. The correction factor for atoms produced above the exobase is about 0.90. Attenuation is more important for atoms reflected several times from the lower atmosphere. The factor in this case ranges from 0.70 in the vicinity of the terminator to about 0.30 at midnight. A bulge is also observed for He (Niemann *et al.*, 1980), with a distribution in local time similar to H. Collisions with He account for additional attenuation of about 8%.

The source of H^* depends critically on the choice of models for the ionosphere. The flux of O^* to the exosphere is determined by recombination of O_2^+ and electrons, and the corresponding production of H^* by (3) is similarly sensitive to ionospheric detail. The source of H^* due to (1) depends on the density and temperature of H^+ . The ionosphere is fairly constant in the region of interest on the dayside. Average profiles from Theis *et al.* (1980) were used, with a 20% correction factor applied to provide consistency with the choice of ionization rates (Torr *et al.*, 1979) and model for the neutral atmosphere. Conditions on the nightside are more complex. Measurements of the total ion density on the nightside of Venus were obtained by the Orbiter Electron Temperature Probe (OETP) (Brace *et al.*, 1979; Theis *et al.*, 1980), the Orbiter Retarding Potential analyzer (ORPA) (Knudsen *et al.*, 1979; Miller *et al.*, 1980), and the Orbiter Radio Occultation experiment (ORO) (Kliore *et al.*, 1979). Ion composition was measured by the Orbiter Ion Mass Spectrometer (OIMS) (Taylor *et al.*, 1979c, 1980). Most of the measurements from the OETP and ORPA experiments which have appeared in the literature to date pertain to altitudes greater than 160 km, well above the O_2^+ peak. We adopt, therefore, results from the OIMS and ORO experiments, which extend to lower altitudes. These measurements resolve the nightside ion peak.

Nightside ion densities show considerable variability from orbit to orbit, ranging from well-established profiles with large ion concentrations and smooth variations with altitude, to depressed conditions under which ion concentrations are much lower and quite variable as functions of altitude (Taylor *et al.*, 1979c). Results from OIMS differ somewhat from ORO. Some of the profiles from OIMS show O_2^+ peak densities as large as 10^5 cm^{-3} near 150 km (Taylor *et al.*, 1980), while results from ORO have peak densities of the order of 10^4 cm^{-3} near 140 km. The mass spectrometric data

pertain to latitudes near 15°N , while the radio occultation passes emphasize regions at high latitudes. Taylor *et al.* (1982), however, showed reasonable agreement between OIMS and ORO for orbit 58, when regions sampled by the two experiments were almost coincident.

Two possible sources have been proposed to account for the observed nightside ionization: subsidence of O^+ transported across the terminator from the dayside (Spencer *et al.*, 1981) and precipitation of high energy electrons from the wake region. (Gringauz *et al.*, 1979; Kumar *et al.*, 1982; Taylor *et al.*, 1982). Densities of O_2^+ as large as 10^4 cm^{-3} can be supported with a downward flux of O^+ of magnitude $2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ averaged over the nightside (Spencer *et al.*, 1981; Cravens *et al.*, 1983). Such a flux would be consistent with the measurements of O^+ transported across the terminator as reported by Knudsen *et al.* (1980). Magnitudes for both of the proposed nightside ionization mechanisms should be sensitive to details of the interaction of Venus with the solar wind, and one might expect therefore, as observed, considerable variability in the resulting ionosphere.

We shall consider, thus, two representative profiles assumed to bracket the possible range of average nightside ion concentrations: the profile obtained in orbit 65 by OIMS at a solar zenith angle of 162° (Taylor *et al.*, 1980), and the average profile suggested by ORO

(Kliore *et al.*, 1979). Densities of O_2^+ for the ORO profile were obtained assuming that the ratio $n(\text{O}_2^+)/n_e$ is equal to the corresponding ratio from OIMS at an equivalent ion scale height displacement from the ionospheric peak.

Profiles adopted for H^+ in the midnight region are shown in Fig. 5. These data are from Taylor *et al.* (1980), orbit 65, up to 300 km, extrapolated logarithmically to higher altitude. The behavior of H^+ across the nightside is similar to that described earlier for nightside H. Profiles of H^+ were assumed to be uniform on the dayside and were taken from Taylor *et al.* (1980, orbit 185). We used measurements of ion temperature by ORPA (Miller *et al.*, 1980) sorted by solar zenith angle, grouped in intervals of 30° . Ion temperatures increase rapidly to 300 km, and are approximately constant above. Boundary temperatures lie between 2000 and 2300 K for solar zenith angles less than 150° , and increase to 5000 K near midnight. Data adopted for present purposes are shown in Fig. 5.

6. RESULTS

We consider three models as summarized in Table 2. Model 1 emphasizes production of H^* by reaction (3). Model 2 includes the contribution from reaction (3) on the dayside, with a dominant contribution from (1) on the nightside. Model 3 has features of both Models 1

FIG. 5. DENSITIES AND TEMPERATURES FOR H^+ ON THE NIGHTSIDE. Densities are taken from Taylor *et al.* (1980) for orbit 65; temperatures, from Miller *et al.* (1980).

TABLE 2. MODELS USED IN CALCULATIONS

Model	Region 1 90°–120° Source	Region 2 120°–150° Source	Region 3 150°–180° Source	n_H (cm ⁻³) 250 km
Model 1	O* + H (ORO)	O* + H (ORO)	O* + H (OIMS)	1×10^5
Model 2	O* + H (ORO)	O* + H (ORO)	O* + H (ORO)	1×10^5
	H ⁺ + H	H ⁺ + H	H ⁺ + H	
Model 2A	O* + H (ORO)	O* + H (ORO)	O* + H (ORO)	5×10^4
	H ⁺ + H	H ⁺ + H	H ⁺ + H	
Model 2B	O* + H (ORO)	O* + H (ORO)	O* + H (ORO)	1.3×10^5
	H ⁺ + H	H ⁺ + H	H ⁺ + H	
Model 3	O* + H (ORO)	O* + H (ORO)	O* + H (1/2 × OIMS)	1×10^5
	H ⁺ + H	H ⁺ + H	H ⁺ + H	

Notes: Density of cold hydrogen at 250 km was used to scale total hydrogen concentrations throughout the planet. ORO denotes hot O fluxes obtained from the Orbiter Radio Occultation average profile of Kliore *et al.* (1979). OIMS denotes hot O fluxes obtained from the Orbiter Ion Mass Spectrometer profile of orbit 65 (Taylor *et al.*, 1980). The charge exchange source is calculated using the H⁺ and H profiles discussed in Section 5.

and 2, including contributions from reactions (1) and (3) on both day and nightsides of the planet.

Model 1

We assume in Model 1 that the radio occultation profile is valid for solar zenith angles between 90 and 150°, while the profile of Taylor *et al.* (1980), orbit 65, is adopted for the midnight region between 150° and 180°. This procedure is consistent with measurements from ORO and OIMS. The thermal H profile was obtained by the method discussed above and was scaled to give a concentration of 1×10^5 cm⁻³ at 250 km at noon. Contributions from the charge exchange source were not included in Model 1.

Profiles for H* are shown in Figs. 6a for noon, 6b for the terminator and 6c for midnight. Results for the noon and midnight calculations are compared with corresponding profiles derived by Wallace (1969), Anderson (1976) and Takacs *et al.* (1980). Error bars in the Anderson dayside profile reflect the spread of temperatures obtained in his analysis of Lyman- α at the bright limb. The results of Bertaux *et al.* (1982), for the south polar region, and the dark disk data of Anderson (1976) were selected for comparison with model results at the terminator.

Our calculated noon profile is in excellent agreement with Anderson's results for the bright limb. The terminator calculations are in similarly good accord with the polar data. On the other hand, observations for the dark disk suggest densities a factor of 3–4 higher than model values. Takacs *et al.* (1980) proposed that as much as two-thirds of the dark disk emission observed by *Mariner 5* could be attributed to backscattering of

light by H in the lower atmosphere; correction for this effect would reduce Anderson's densities by a factor of 2–3, bringing them into closer agreement with results in Fig. 6b.

The model results for midnight also fall below Anderson's *Mariner 5* data for the dark disk. The

FIG. 6a. HOT HYDROGEN DENSITIES ON THE DAYSIDE FROM MODEL 1.

The profiles of Wallace (1969), Anderson (1976) and Takacs *et al.* (1980) are included for comparison. The error bars in Anderson's profile are calculated from his range in temperatures. The results of our calculation are shown by the thick solid line.

FIG. 6b. HOT HYDROGEN DENSITIES AT THE TERMINATOR FROM MODEL 1.

The profiles of Anderson (1976) and Bertaux *et al.* (1982) are included for comparison.

calculated scale height is similar to that derived by Takacs *et al.* (1980) for *Mariner 10*, but densities in the model are a factor of 2 higher than observation. Wallace's (1969) profile for *Mariner 5* is similar to present calculations at high altitudes, but his densities are a factor of 3 lower at 10,000 km. The spread

exhibited by the different experimental profiles suggests that nightside exospheric hydrogen may be quite variable. Takacs *et al.* (1980), for example, indicate temperatures for H^* ranging from 600 to 1000 K, with densities at the exobase from 1.5 to $2.5 \times 10^3 \text{ cm}^{-3}$. These parameters permit a range of densities for H^* at 10,000 km as large as a factor of 2 for conditions during the flyby of *Mariner 10*.

Model 2

Results for Model 1 indicate that the observed density of H^* can be supplied by reaction (3) alone. Contributions from the charge exchange process (1) were not included in Model 1 but must be incorporated in a more complete model for Venus' hydrogen. They are included in Model 2.

The radio occultation profile is assumed to apply throughout the nightside. We allow for production of H^* by (1) using profiles for H^+ and H described previously, scaled to a noon H density of $1 \times 10^5 \text{ cm}^{-3}$ at 250 km. The ionospheric peak in the profile from ORO has a lower density and is located at a lower altitude than from OIMS profile used in Model 1. Consequently, the nightside source of H^* is dominated by (1) in Model 2.

Results for Model 2 are shown by the thick lines in Fig. 7a (dayside), 7b (terminator) and 7c (nightside). The dayside results are again in excellent accord with Anderson (1976). Model results for the terminator and nightside are also consistent with observation. We

FIG. 6c. HOT HYDROGEN DENSITIES AT MIDNIGHT FROM MODEL 1.

The profiles of Wallace (1969), Anderson (1976) and Takacs *et al.* (1980) are included for comparison.

FIG. 7a. HOT HYDROGEN DENSITIES AT NOON FROM MODELS 2, 2A AND 2B.

The results of Models 2A and 2B are shown by the solid dots. See Fig. 6a.

FIG. 7b. HOT HYDROGEN DENSITIES AT THE TERMINATOR FROM MODELS 2, 2A AND 2B.
See Fig. 6b.

considered two modifications to Model 2, denoted by Models 2A and 2B. The nightside ionospheric profiles are the same in 2A and 2B as in 2, but the densities of thermal H were scaled differently. Model 2A assumed a noon H density of $5 \times 10^4 \text{ cm}^{-3}$ at 250 km, in close agreement with Brinton *et al.* (1980) and Bertaux *et al.* (1982). This model provides the minimum amount of

exospheric H^* consistent with observation. The density of thermal H at noon was taken as $1.3 \times 10^5 \text{ cm}^{-3}$ at 250 km in Model 2B, providing an upper bound to the level of thermal H consistent with the high altitude observations. Profiles of H^* for Models 2A and 2B, are shown by the solid black dots in Fig. 7.

Model 3

All of the important processes are incorporated in a self-consistent fashion in Model 3. We adopt H^+ and H densities as above for the charge exchange process, with a density for thermal H at noon equal to $1 \times 10^5 \text{ cm}^{-3}$. The nightside ionosphere is similar to that in Model 1. The profile from ORO was used for zenith angles between 90° and 150° . The OIMS profile was adopted between 150° and 180° , but the corresponding H^* source was reduced by a factor of 2. (This adjustment is required since the H^* source from (3) would be otherwise unacceptably large.) Figures 8a, 8b and 8c show corresponding results for noon, terminator and midnight regions as before. Calculated profiles are again in satisfactory agreement with observation.

Relative contributions from (1) and (3) to H^* on both day and nightsides are shown in Fig. 9 for Model 3, distinguishing contributions from the sunlit and dark ionospheres. The concentration of H^* at low altitudes on the dayside is set mainly by collisions of H with O^* on the dayside. Reaction (1) on the nightside provides an important contribution to dayside H^* at radial distances larger than 18,000 km. Reaction (1) accounts

FIG. 7c. HOT HYDROGEN DENSITIES AT MIDNIGHT FROM MODELS 2, 2A AND 2B.
See Fig. 6c.

FIG. 8a. HOT HYDROGEN DENSITIES AT NOON FROM MODEL 3.
See Fig. 6a.

FIG. 8b. HOT HYDROGEN DENSITIES AT THE TERMINATOR FROM MODEL 3.
See Fig. 6b.

for approximately half of the nightside H^* , with the balance derived from (3) with contributions from this reaction on both day and nightsides of the planet.

Figure 10 illustrates the importance of inter-hemispheric transport. Contributions from day and nightside sources are shown for H^* at noon (Fig. 10a)

FIG. 8c. HOT HYDROGEN DENSITIES AT MIDNIGHT FROM MODEL 3.
See Fig. 6c.

FIG. 9. CONTRIBUTIONS TO THE HOT HYDROGEN DENSITY ON DAY (NOON) AND NIGHTSIDES (MIDNIGHT) FROM $H^+ + H$ SOURCES, $O^* + H$ DAYSIDE SOURCES, AND $O^* + H$ NIGHTSIDE SOURCES.

We have used results from Model 3.

and midnight (Fig. 10b), again using the parameters of Model 3. Suprathermal H originating on the nightside makes a dominant contribution to H^* at planetocentric distances larger than 18,000 km at noon. Nightside sources account for the bulk of H^* at all altitudes near midnight.

The contribution to H^* due to reflection of fast atoms by the lower atmosphere is illustrated in Fig. 11. The solid lines represent the density of H^* expected in the absence of reflection. The additional contribution from reflection is shown by the dashed lines. Reflected atoms make a significant contribution to H^* , comparable to the primary source, at low altitudes, especially on the nightside. The average energy of reflected atoms is less than that of primary H^* . The scale height of the reflected component is reduced accordingly.

7. DISCUSSION

The preceding analysis indicates that the distribution of suprathermal H observed in Venus' exosphere may be attributed to a combination of sources due to reactions (1) and (3). There is no need to

FIG. 10. CONTRIBUTIONS TO THE HOT HYDROGEN DENSITY ON DAY AND NIGHTSIDES FROM DAYSIDE AND COMBINED NIGHTSIDE SOURCES OF MODEL 3.

FIG. 11. CONTRIBUTIONS TO THE HOT HYDROGEN DENSITY ON DAY AND NIGHTSIDES FROM ATOMS UNDERGOING NO COLLISIONS, AND FROM ATOMS REFLECTED BY THE LOWER ATMOSPHERE (MODEL 3).

invoke additional contributions from reactions involving H_2 . Reactions (1) and (3) contribute in approximately equal proportions to the global source of H^* .

Lateral transport across the terminator in the exosphere plays a major role in regulating the distribution of H , both thermal (Mayr *et al.*, 1980; Hodges and Tinsley, 1982) and suprathermal. It contributes to the bulge in thermal H observed in the predawn sector, influencing in turn the magnitude of the suprathermal nightside source. Reaction (1) on the nightside makes an important contribution to H^* on the dayside at planetocentric distances larger than 18,000 km. Its importance is due in part to the high density of thermal H on the nightside, in part to the high observed density of H^+ and the high ion temperatures observed in the source region near midnight.

Elevated temperatures and densities of H^+ in the antisolar region must be attributed ultimately to the interaction of Venus with the solar wind. Plasma is advected at high speed, more than 1 km s^{-1} , across the terminator (Knudsen *et al.*, 1980). Thermalization near midnight can account for the energy source required to maintain the high temperature of H^+ (Knudsen *et al.*, 1980). Subsidence of advected O^+ represents the

dominant source of ionization over much of the nightside, although high energy electrons may also contribute in localized regions (Kumar *et al.*, 1982; Taylor *et al.*, 1982). We expect the supply and energetics of nightside ionization to respond to changes in solar wind. These changes should be reflected in comparable fluctuations in the source of nightside H^* , leading to variations in the concentration of H^* at large distances from the planet. Observations of Lyman- α under different solar wind and nightside ionospheric conditions should provide therefore an excellent test of the model developed here.

Escape fluxes of H are presented in Table 3. Fluxes in

TABLE 3. HYDROGEN ESCAPE FLUXES

	Ionospheric source ($\text{cm}^{-2} \text{ s}^{-1}$)	Total flux ($\text{cm}^{-2} \text{ s}^{-1}$)
Model 1	1.5×10^6	4.0×10^6
Model 2	5.0×10^6	7.5×10^6
Model 2A	2.5×10^6	3.8×10^6
Model 2B	6.5×10^6	9.5×10^6
Model 3	5.2×10^6	7.7×10^6

the first column reflect contributions from reactions (1) and (3). Other processes, charge transfer with solar wind for example, contribute an additional flux of $2.5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ (McElroy *et al.*, 1982a). Table 4 shows a breakdown of contributions from different regions and different reactions in Model 3.

Observations of Lyman- α provide important constraints on the rate at which hydrogen escapes from Venus. Escape fluxes in Table 3 range from 4 to $9.5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, depending on the choice of ionospheric model. Reaction (1) provides a more efficient means for escape of H than reaction (3), as might have been anticipated from the velocity distributions shown in Fig. 2. Largest escape fluxes consistent with present observations of Lyman- α arise if the source of H^* due to (3) on the nightside is negligible. Most of the escaping hydrogen atoms originate on the nightside, between solar zenith angles of 120 and 180°, reflecting a combination of high ion temperatures, elevated densities of H and H^+ and enhanced fluxes of O^* . Results depend quite sensitively on assumptions made regarding the structure of the nightside ionosphere. Variations in excess of an order of magnitude have been observed in the densities of nightside H^+ and O_2^+ (Taylor *et al.*, 1980) and this variability will be reflected in comparable fluctuations in rates of escape. We should note that Lyman- α profiles obtained in the various Venus missions provide merely snapshots of conditions in Venus' exosphere. The ionospheric data adopted here were obtained by *Pioneer Venus*, at a different time from the Lyman- α observations used for comparison with our model

results from H^* . This could lead to some ambiguity in our results and associated errors in estimates for the escape rate of H.

Escape rates of H derived here are less than values obtained by other investigators. Kumar *et al.* (1981) estimated a flux of $1 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ from dissociative recombination of OH^+ . As noted earlier we expect that the contribution from this process should be less than $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ if more realistic mixing ratios are adopted for H_2 . Hodges and Tinsley (1981) and Kumar *et al.* (1983) estimated a flux of $2 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$. The discrepancy in this case reflects the choice of higher densities for H^+ on the nightside. Higher densities of nightside H^+ lead to unacceptably large concentrations of H at large distances on the dayside, with consequent discrepancies between calculated and observed profiles of Lyman- α . [Hodges and Tinsley's analysis was restricted to radial distances less than 13,000 km; constraints posed by Lyman- α were not explicitly considered by Kumar *et al.* (1983).]

The rate of loss of H in Table 3 is consistent with the value of about $10^7 \text{ cm}^{-2} \text{ s}^{-1}$ required to maintain a stoichiometric balance between escape of H and O supplied by evolution of H_2O (McElroy *et al.*, 1982b). The present model suggests escape of O at a rate of $6 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$. A literal interpretation of stoichiometric balance would require H escape at a rate of $1.2 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$, in satisfactory agreement with model 2B. We should emphasize, however, that stoichiometric balance need not apply instantaneously. It should hold rather on time scales characteristic either of changes in the oxidation state of the entire atmosphere or, more likely, time scales corresponding to variations in the rate of supply of H to the upper atmosphere. Time scales for change in the oxidation state of the atmosphere are long, of order 10^8 years; changes in the concentration of hydrogen bearing gases above the main cloud deck could occur more rapidly, however, on time scales as short as 10^4 years.

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Note added in proof—A more complete empirical model of the Venus ionosphere based on OETP data and extending down to an altitude of 150 km has recently been published (Theis *et al.*, 1984). The updated ion densities are consistent with ORO values and their use would not affect the results presented here.

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TABLE 4. HYDROGEN ESCAPE FLUXES FOR MODEL 3

	Planetary escape flux ($\text{cm}^{-2} \text{ s}^{-1}$)	
Day (direct)	7.6×10^5	
Day (reflected)	1.8×10^5	
Total day		9.4×10^5
Region 1 ($\text{O}^* + \text{H}$)	5.6×10^3	
Region 1 ($\text{H}^+ + \text{H}$)	8.0×10^4	
Region 1 (reflected)	1.8×10^4	
Total Region 1		1.0×10^5
Region 2 ($\text{O}^* + \text{H}$)	3.4×10^3	
Region 2 ($\text{H}^+ + \text{H}$)	1.3×10^6	
Region 2 (reflected)	2.3×10^5	
Total Region 2		1.5×10^6
Region 3 ($\text{O}^* + \text{H}$)	2.2×10^5	
Region 3 ($\text{H}^+ + \text{H}$)	1.9×10^6	
Region 3 (reflected)	5.6×10^5	
Total Region 3		2.7×10^6
Total escape flux from ionospheric sources		5.2×10^6

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APPENDIX—FORMULATION OF THE TRANSPORT PROBLEM FOR NON-THERMAL ATOMS

The problem of "hot" atom transport in the region below the exobase is conceptually similar to the photoelectron problem treated by Prather *et al.* (1978). Because of the limited extent of the production region below the exobase, we can assume that non-thermal particles travel in straight lines in a plane-parallel atmosphere. The specific intensity is then a function of three variables: z , altitude; μ , cosine of the angle of the velocity with the vertical; and E , energy. The transport equation is then of the form

$$\mu \frac{\partial I(E, \tau, \mu)}{\partial \mu} = I(E, \tau, \mu) - \bar{\omega}(E, \tau) \times \int_{-1}^{+1} P_{e1}(\mu, \mu') I(\mu') d\mu' - S(E, \tau, \mu), \quad (A.1)$$

with

$$d\tau(E, z) = -K(E, z) dz, \quad (A.2)$$

$$\bar{\omega}(E, \tau) = X(E, \tau)/K(E, \tau), \quad (A.3)$$

and

$$S(E, \tau, \mu) = \frac{\bar{S}_0(E, \tau, \mu) + \bar{S}'(E, \tau, \mu)}{K(E, \tau)}, \quad (A.4)$$

where $I(E, \tau, \mu)$ is the specific intensity ($\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1} \text{ster}^{-1}$); $K(E, \tau)$ denotes the inverse of the collision mean free path; $X(E, \tau)$ is the inverse of the mean free path limited to elastic scattering; $P_{e1}(E, \mu, \mu')$ defines the probability of elastic scattering from μ to μ' ; $\bar{S}_0$ represents the source of primary atoms ($\text{cm}^{-3} \text{s}^{-1} \text{eV}^{-1} \text{ster}^{-1}$); and $\bar{S}'$ is the source at energy E due to cascade from higher energies.

To evaluate all of the above quantities, we need first to consider the kinematics of hot atoms colliding with atmospheric species. We assume that the latter are at rest in the Venus reference frame: thermal velocities at 300 K are much smaller than typical speeds for non-thermal atoms. The energy E of the fast atoms after a collision is given by (Libby, 1947)

$$E = E_0[\rho^2 + (1 - \rho)^2 + 2\rho(1 - \rho) \cos \theta_c] \quad (A.5)$$

with

$$\rho = \frac{M}{M + M'}, \quad (\text{A.6})$$

where E_0 is the initial energy; M denotes the mass of the hot atom; M' is the mass of the target, and θ_c is the scattering angle in the center of mass frame.

We find, from (A.6), that the energy interval corresponding to a scattering angle differential $d \cos \theta_c$ may be written in the form

$$dE = 2\rho(1 - \rho)E_0 d(\cos \theta_c). \quad (\text{A.7})$$

If scattering is isotropic in the center of mass frame, the probability, $p(E_0, E) dE$, of scattering from an energy E_0 into an interval dE around E is given by

$$p(E_0, E) dE = \frac{d(\cos \theta_c)}{2} = \frac{dE}{4\rho(1 - \rho)E_0}. \quad (\text{A.8})$$

We may express the angular differential cross-section for scattering from an energy E_0 to E as

$$\Phi(E_0, E, \mu_0, \mu) = \int_0^{2\pi} \frac{\delta(\cos \theta - \cos \theta_L)}{2\pi} d\phi, \quad (\text{A.9})$$

where

$$\cos \theta = \mu_0 \mu + (1 - \mu_0^2)^{1/2} (1 - \mu^2)^{1/2} \cos(\phi - \phi_0), \quad (\text{A.10})$$

the cosine between the direction (μ_0, ϕ_0) and (μ, ϕ) , is given by the usual angle-addition formula and θ_L is the scattering angle in the Venusian rest frame. The expression for θ_L in terms of θ_c generally involves the solution of a set of transcendental equations (Corben and Stehle, 1960, p. 62); however, in two special cases, θ_L may be reduced to a simple function of θ_c :

$$\theta_L = \theta_c, \quad \text{for } M \ll M',$$

and

$$\theta_L = 1/2, \quad \text{for } M = M'. \quad (\text{A.11})$$

The differential cross-section given by (A.9) is highly anisotropic, and incorporating its full expression in the transport solution would lead to unnecessary complexity. We shall substitute a more tractable approximate expression for Φ preserving the essential features of the differential scattering cross-section. The approach has been used elsewhere in radiative transfer theory under the general title of similarity relations (Sobolev, 1975, p. 158). The approximate differential cross-section is written in the form

$$\Phi_0(E_0, E, \mu_0, \mu) = [(1 - r(E_0, E) + 2r(E_0, E)\delta(\mu_0 \pm \mu)]/2, \quad (\text{A.12})$$

which assumes that a fraction r of the particles are either forward- or back-scattered, while $1 - r$ are scattered isotropically. The factor of 2 in the second term of (A.12) is introduced for purposes of normalization.

We choose weights $r(E_0, E)$ of the form

$$r(E_0, E) = |\cos \theta_L(E_0, E)|^n, \quad (\text{A.13})$$

with $\cos \theta_L$ obtained from (A.11) and (A.5). The δ -function component of Φ_0 is taken to be forward, $\delta(\mu_0 - \mu)$, for $\cos \theta_L$ greater than 0, and backward, $\delta(\mu_0 + \mu)$, for $\cos \theta_L$ less than 0. This choice permits scattering to be isotropic for situations when the rest frame scattering angle is 90° ; equation (A.12) allows scattering in the forward and back directions under the

same conditions as in the original problem [$\cos(\theta_L) = \pm 1$]. In other situations, the weight given to the isotropic scattering component depends on the exponent n : higher values of n require that a larger fraction of the particles be scattered isotropically.

Calculations were carried out with $n = 1/2, 1, 2$ and 3 ; we found that changing the value of n altered the results by less than 5%. Thus solutions are relatively insensitive to the detailed shape of the differential cross-section.

The energy range was divided into N equally spaced bins with mean energies $0 < E_1 < E_2 < \dots < E_N$ and width ΔE . The term $\cos \theta_L(E_0, E)$ in (A.13) was replaced by $\cos \theta_L(E_i, E_j)$, the average value of $\cos \theta_L$ for scattering from bin E_i to bin E_j . The average was obtained by convolving the expression for $\cos \theta_L(E_0, E)$ with the probability function $p(E_0, E)$ given by (A.8).

The primary production function $S_0(E, \tau, \mu)$, for fast O atoms is given by

$$\bar{S}_0(E_0, \tau, \mu) = \frac{2k_1 n_{O_2^+}(\tau) n_e(\tau)}{4\pi \Delta E}, \quad (\text{A.14})$$

where $E_0 = 2.5$ eV and $k_1 = 1.6 \times 10^{-9} (T_e/300)^{0.55} \text{ cm}^3 \text{ s}^{-1}$ is the rate constant for dissociative recombination of O_2^+ (Nagy *et al.*, 1980). The production is zero for energies other than E_0 . The primary production is non-zero at all energies for fast H; sources are discussed for this case in Section 4.

The rate of cascade from bin E_i to bin E_j can be derived from (A.8) and (A.6). Atoms are scattered into a continuous range of energies extending down to a minimum energy

$$E_{\min}(i) = [1 - 4\rho(1 - \rho)]E_i. \quad (\text{A.15})$$

In the case of collisions involving similar species (i.e., O* scattering off O), an additional secondary hot atom is produced with energy

$$E_s = E_0 - E, \quad (\text{A.16})$$

where E is obtained from equation (A.5); we can account thus for production of secondaries by doubling the contribution for cascade. The combined source for cascading and secondary particles is then

$$\begin{aligned} \bar{S}'(E_j, \tau, \mu) = & \sum_{\alpha} \sigma_{\alpha} n_{\alpha}(\tau) \sum_k \frac{(\Delta E_{jk})}{4E_k \rho(1 - \rho)} \\ & \times \int_{-1}^1 \Phi_0(E_k, E_j, \mu', \mu) I(E_k, \tau, \mu') d\mu' \times f_{\alpha}, \end{aligned} \quad (\text{A.17})$$

where α denotes the atmospheric species; σ_{α} is the cross-section (cm^2) for collision with species α ; and n_{α} represents the density (cm^{-3}) at τ . The index k spans all higher energy bins E_k which cascade into E_j . The bin size ΔE_{jk} is equal to ΔE if $E_{\min}(k) \leq E_j - \Delta E/2$; otherwise

$$\Delta E_{jk} = E_j + \frac{\Delta E}{2} - E_{\min}(k). \quad (\text{A.18})$$

The differential scattering cross-section, $\Phi_0(E_k, E_j, \mu', \mu)$, is given by (A.12); f_{α} equals 2 when additional secondary atoms are produced, with f_{α} equal to 1 in all other cases.

Elastic scattering corresponds to particles which stay within the same bin after scattering. The differential cross-section in this case is decomposed as before (A.12) into isotropic and forward-peaked contributions. Forward elastic scattering is a

null process, however. We take $P_{e1}(\mu', \mu) = \frac{1}{2}$ (isotropic scattering), and, using the probability function derived in (A.8), we find

$$X(E_j, \tau) = \sum_{\alpha} \sigma_{\alpha} n_{\alpha}(\tau) \int_{(E_j - \Delta E/2)}^{(E_j + \Delta E/2)} \frac{dE_0}{\Delta E} \times \int_{E_0 - \Delta E/2}^{E_0} p(E_0, E') dE' [1.0 - \overline{\cos^2 \theta_L(E_j, E_j)}]. \quad (\text{A.19})$$

The factor $[1.0 - \overline{\cos^2 \theta_L}]$ accounts for the isotropic scattering component; the double integral defines the fraction of atoms staying in the bin after one scattering.

The above form assumes that, for all energies within bin E_i , there exists a range of angles for which the particles are scattered out of the bin. In the case of light atoms scattered by much heavier species, the range of final energies is small, and above some energy E_1 all particles remain within the bin after

one scattering. In this case (A.19) is modified to

$$X(E_j, \tau) = \sum_{\alpha} \sigma_{\alpha} n_{\alpha}(\tau) \left[\int_{(E_j - \Delta E/2)}^{E_1} \frac{dE_0}{\Delta E} \times \int_{(E_j - \Delta E/2)}^{E_0} p(E_0, E') dE' + \int_{E_1}^{(E_j + \Delta E/2)} \frac{dE_0}{\Delta E} \times \int_{E_0[1 - 4\rho(1 - \rho)]}^{E_0} p(E_0, E') dE' \right] \times [1 - \overline{\cos^2 \theta_L}]. \quad (\text{A.20})$$

The inverse of the collisional mean free path is obtained by adding the inelastic scattering contribution to the isotropic component of the intra-bin scattering calculated in (A.19). Thus,

$$K(E_j, \tau) = \sum_{\alpha} \sigma_{\alpha} n_{\alpha}(\tau) - \frac{\overline{\cos^2 \theta_L(E_j, E_j)}}{[1.0 - \overline{\cos^2 \theta_L(E_j, E_j)}]} X(E_j, \tau). \quad (\text{A.21})$$