Hot hydrogen in the exosphere of Venus

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The Ly α measurements of the hydrogen corona of Venus by Mariners 5 (ref. 1) and 10 (ref. 2) have been shown to be consistent with a two temperature component model. Bertaux *et al.*[3] have successfully fitted the Venera 9 exospheric Ly α data with an elevated (500 K) single temperature; however, they also indicated that their data are not inconsistent with a two component model. Various source mechanisms have been proposed to explain the 'hot' (~1,000 K), energetic component of the hydrogen corona. Here we use recent results from the Pioneer Venus Orbiter (PVO)[4] to establish the major sources of this hot hydrogen population.

The most viable of the suggested source mechanisms were reviewed and re-evaluated by Kumar *et al.*[5], who concluded that the exothermic reaction,

$$O^+ + H_2 \rightarrow OH^+ + H\ (<0.6\ \text{eV}) \quad (1)$$

is the major source of the 'hot non-thermal' hydrogen. The subsequent recombination of OH^+ produces extremely energetic (~8 eV) hydrogen which makes only an insignificant contribution to the observed hot hydrogen, although it is the major contributor to the non-thermal escape flux.

Kumar *et al.*[5] also indicate that the reaction

$$CO_2^+ + H_2 \rightarrow CO_2H^+ + H\ (<1.17\ \text{eV}) \quad (2)$$

can also make a modest contribution to the non-thermal population. Sze and McElroy[6] considered the charge exchange reaction:

$$H^+_{hot} + O \rightarrow O^+ + H_{hot} \quad (3)$$

and Kumar *et al.*[5], Chamberlain[7] and Stewart[8] considered:

$$H^+_{hot} + H \rightarrow H^+ + H_{hot} \quad (4)$$

where the hot hydrogen ion could be a solar wind ion or a hot ionospheric ion. These two charge exchange reactions were found to be unimportant for the hot hydrogen population, although reaction (4) was found to contribute to the non-thermal escape flux.

The very comprehensive ionospheric data base, which is now becoming available from the instruments on board the PVO[4] provides a new opportunity for a re-evaluation of the various proposed source mechanisms for the hot hydrogen corona. This letter has two purposes: first, to point out that reactions (3) and (4), as well as (1), are, in light of the PVO results, important sources of hot H from the nightside. Previous studies have never really explained why there was almost as much hot hydrogen observed by Mariner 5 (ref. 1) on the nightside of Venus as there is on the dayside. Ferrin[9] indicated that horizontal transport of hot hydrogen from the dayside might contribute, but he was puzzled by the fact that the nightside non-thermal H seems to be even hotter than the dayside one (1,500 K on the nightside and 1,025 K on the dayside according to Anderson[1]). We will show that the relatively large H^+ and O^+ densities[10] and high ion temperatures[11] (~5,000 K) observed by PVO on the nightside enhance the importance of reactions (3) and (4). Second, we re-evaluate the sources of hot H on the dayside of Venus, in light of the PVO results and conclude that the sources previously proposed are adequate.

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Kumar *et al.*[5] calculated column production rates for various potential sources of hot hydrogen to assess their relative importance. To evaluate the hot hydrogen density at the exobase one must take into account collisions of the hydrogen atoms with the cold background gas. Ferrin[9] accomplished this by using Monte Carlo calculations and a multistream approach. He showed, by assuming a hard sphere collision model, that the inclusion of such collisions and the subsequent energy cascading results in significant enhancements of the calculated hot hydrogen densities. In the present work, we used a two stream approach, employed widely in radiative transfer[12] and photoelectron calculations[13], to evaluate the hot hydrogen fluxes and densities on Venus. The equations solved are:

$$\langle\cos\theta\rangle \frac{d\phi^+(E,z)}{dz} = -\sum_i n_i\sigma_i\phi^+(E,z) + \frac{P}{2} + P^+$$
$$-\langle\cos\theta\rangle \frac{d\phi^-(E,z)}{dz} = -\sum_i n_i\sigma_i\phi^-(E,z) + \frac{P}{2} + P^- \quad (5)$$

where $\phi^+(E,z)$ is the upward directed hot hydrogen flux; $\phi^-(E,z)$ the downward directed hot hydrogen flux; $n_i(z)$ the *i*-th scattering atmospheric constituent; z the altitude; σ_i the total scattering cross-section for species i; $\langle\cos\theta\rangle$ the mean of the cosine of the angle of the hydrogen velocity vector with respect to the vertical (assumed to be 0.5, corresponding to an isotropic distribution); P the hot hydrogen production rate due to the various sources under consideration (assumed isotropic); and $P^{\pm}$ the 'production' rates at a given energy due to cascading from collisions at higher energies.

The energy distribution function, $f(E, z)$, can be determined from the calculated flux values, through the following relationship:

$$f(E,z) = \{\phi^+(E,z) + \phi^-(E,z)\}/v(E) \quad (6)$$

where $v(E)$ is the hydrogen velocity corresponding to energy E.

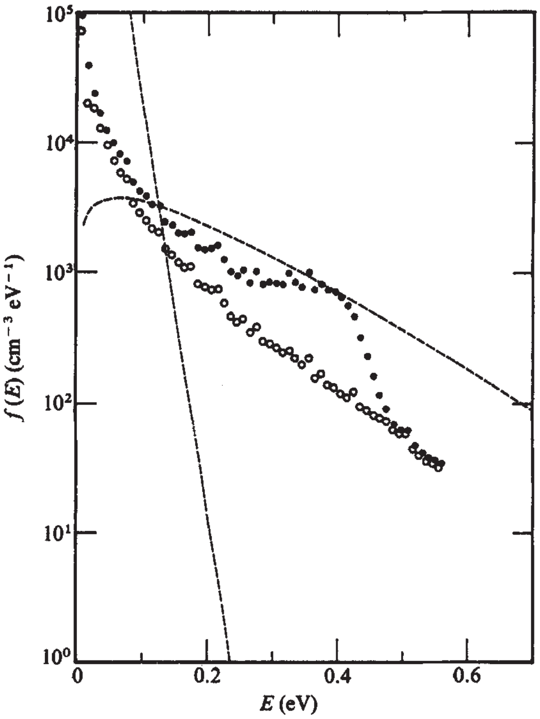

Fig. 1 The total calculated nightside density distribution function (●) is shown. ○, The distribution function including only the charge exchange reactions (3) and (4). The dashed lines represent the two component distribution functions deduced by Anderson[1] ($n = 2\times10^5$ cm^{-3} and $T = 150$ K for the cold and $n = 1\times10^3$ cm^{-3} and $T = 1{,}500$ K for the hot component).

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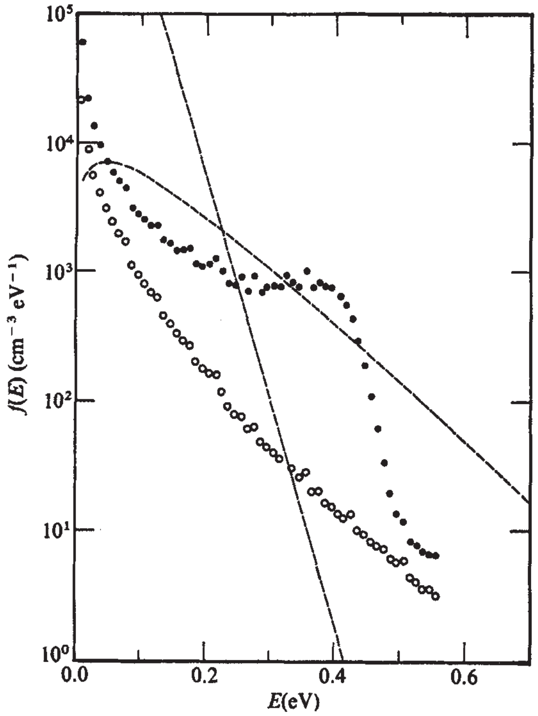

Fig. 2 The total calculated dayside density distribution function (●) is shown. ○, The distribution function including only the charge exchange reactions (3) and (4). The dashed lines represent the two component distribution functions deduced by Anderson[1] ($n = 2\times10^5$ cm^{-3} and $T = 275$ K for the cold and $n = 1.3\times10^3$ cm^{-3} and $T = 1,025$ K for the hot component).

The hot hydrogen atoms were assumed to be 'lost' either by escape at the topside or through a series of energy losses due to elastic hard sphere collisions[14] with the background gases (CO_2, O, H), eventually becoming part of the cold hydrogen population. We have neglected the small but finite probability of energy gain through these collisions. The average energy losses in backward and forward elastic scattering events are[14]

$$\overline{\Delta E_b} = \frac{3mM}{(m+M)^2} E_{in} \quad \text{and} \quad \overline{\Delta E_f} = \frac{mM}{(m+M)^2} E_{in}$$

respectively and where m is the mass of an H atom, M is the mass of the target and E_{in} is the initial H atom energy.

The appropriate neutral gas and ion densities as well as the ion temperatures were taken from Pioneer Venus data[10,11,15], except for the neutral atomic hydrogen densities, for which the Mariner 5 estimate of Anderson[1] was used, and molecular hydrogen, for which the estimate of Kumar and Hunten[16] was used. The adopted values of the dayside Pioneer Venus data correspond to zenith angles of about 70°, while the nightside data correspond to zenith angles of about 140°. The nightside ionospheric data were taken from the outbound segment of Orbit 59. The nightside ionosphere has been found to be extremely variable from orbit to orbit; therefore, the results of these calculations should only be considered as 'representative'.

The energy grid used in the two stream calculations was 0.01 eV and the altitude grid size was variable ranging from 0.2 km below 130 km up to 5 km above 250 km. The upper boundary was at 600 km. To approximate the escaping and ballistic components of the flux, the downward directed flux, ϕ^-, at the upper boundary, was assumed to be equal to the integral of the downward production above this altitude for energies greater than the escape energy (0.56 eV) and equal to the upward flux for lower energies. Although the upper boundary was set at 600 km, scattering by the background gas is not very important above the exobase level which is at about 170 km on the dayside and at about 145 km on the nightside. Consequently, above the exobase (or critical) level the distribution functions calculated using equations (5) and (6) remain almost constant with increasing altitude, because equation (5) only takes into account 'collisional' effects. What we obtain using equation (5) are distribution functions at the exobase level. We assumed that the H atoms from reactions (1) and (2) are produced with less energy than the exothermicities of the reactions would indicate, to take into account some degree of vibrational and/or rotational excitation of the product ions. H atoms from reactions (1) and (2) were assumed to be created with a gaussian distribution; the central energies were taken to be 0.4 eV and 0.8 eV respectively, with an assumed halfwidth of 0.03 eV. The hot H atom densities calculated including the effects of scattering (and cascading) by the background gas are about a factor of three larger than those calculated assuming no scattering and cascading. This is in line with the enhancement values found by Ferrin[9].

Anderson[1] found that he could fit the hot component of Mariner 5 nightside Ly α data by assuming a maxwellian distribution with an exobase density and temperature of 1×10^3 cm^{-3} and 1,500 K respectively. The energy distribution of the total hot hydrogen densities calculated for night-time conditions are shown in Fig. 1; for comparison the contribution due only to reactions (3) and (4) is shown with open circles, and the 'hot' and 'cold' maxwellian components deduced by Anderson[1] are indicated by dashed lines. These calculations indicate that the charge exchange reactions (3) and (4) are the source of about 50% and reaction (1) is the source of the other 50% of the night-time 'hot' hydrogen densities. Overall the calculated distribution function agrees reasonably well both in magnitude and shape with the deduced values in the energy range of 0.12 eV (the crossover point with the cold component) and 0.56 eV (the escape energy). The fact that the calculated distribution is not exactly maxwellian in shape is not of special concern, because the actually observed limb intensities do not uniquely require such a distribution.

The calculated dayside exobase distribution function is shown in Fig. 2 along with Anderson's dayside hot and cold maxwellian distributions. The overall hot density is about the same as the

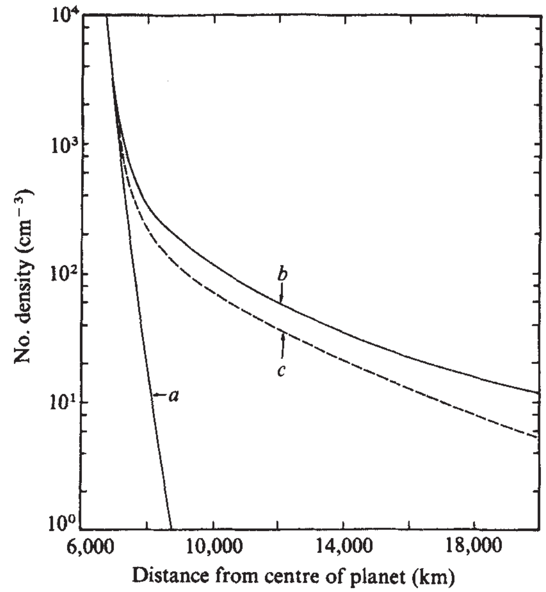

Fig. 3 H number densities for the nightside are shown as functions of the distance from the centre of the planet. *a*, Corresponds to the cold maxwellian of Fig. 1; *b*, is for both the cold and hot maxwellians of Fig. 1; and *c*, is for the cold maxwellian plus the non-maxwellian of Fig. 1.

maxwellian for energies greater than about 0.22 eV and less than 0.57 eV. The charge exchange sources contribute very little to the total hot density on the dayside. The $O^+ + H_2$ reaction is the dominant source of the nonthermal H.

Given a distribution function at the exobase level one can find the corresponding exospheric density distribution of H as a function of altitude by using Liouville's theorem[17]. We calculated the exospheric density distributions, using the distribution functions shown in Figs 1 and 2 and assuming (1) that the distribution functions are isotropic and (2) that there is spherical symmetry. Only ballistic and outgoing (escaping) hyperbolic orbits were included in our calculations. This should be a fairly good assumption because, for Venus, satellite particles will be rapidly removed by charge exchange with energetic solar wind or ionosheath protons. The calculated exospheric densities for the nightside are shown in Fig. 3. The total hydrogen altitude distribution (cold and hot maxwellians), has almost the same shape as density distribution *c* (the cold maxwellian plus our calculated nightside distribution), although the absolute magnitude is somewhat larger. We also calculated the total exospheric altitude distributions for the dayside but do not show them here because of space limitations and because the agreement between our calculated altitude distribution and the one deduced by Anderson[1] agree even better (~20%) than shown for the nightside case.

Note that, in comparing the results of these calculations with the Mariner 5 data, the atmospheric and ionospheric conditions were different during the Mariner 5 encounter and the Pioneer Venus observations and furthermore, the ionospheric densities are highly variable and only model values of H_2 are available. The calculations presented here indicate, within the limitations just mentioned, that reactions (1), (3) and (4) are the major sources of the 'hot' component of Venus hydrogen corona. On the nightside the charge exchange reactions are important because the ion temperatures are high and the H^- densities are greater than on the dayside. There are preliminary indications, from the Pioneer Venus ion mass spectrometer results[10], that there is a significant night-time hydrogen bulge; if the night-time 'cold' hydrogen densities are greater than the values assumed in these calculations, the importance of reaction (4) will increase further. Contrary to earlier suggestions[9], most or at least a significant fraction of the nightside hot hydrogen population is apparently produced locally.

As the Pioneer Venus Ly α intensity results become available, more quantitative comparisons can be carried out. The nightside Venus ionosphere is highly variable, with apparent time scales of the same order as the hot hydrogen lifetime (~10^3 s) and therefore, orbit to orbit comparisons between the measured Ly α intensities and ionospheric parameters can be used to check the validity of the basic mechanisms suggested in this work.

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A weak interaction model for Io and the jovian magnetosphere

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Four features of the interaction between the satellite Io and the surrounding jovian magnetosphere place constraints on the atmosphere of the satellite and on the nature of the interaction: (1) the atmosphere must be at least partly an exosphere so that sodium and other non-volatile atoms sputtered from the surface of the satellite could escape[1,2]; (2) the atmosphere should be dense enough for a detectable ionosphere to form showing a leading–trailing asymmetry[2,3]; (3) the atmosphere should provide an electrically conductive path to produce the electric currents which eventually cause the Io-related decametric radio emissions[4,5]; (4) the conductivity of the ionosphere should not be large enough to short out the electric field seen by the satellite, as pronounced absorption of energetic particles is observed[6–8]. Before the Pioneer 10 encounter it was pointed out[9] that erosion by the co-rotating magnetosphere caused atmospheres on the galilean satellites with surface pressures in the range 10^{-5}–10^{-9} mbar, if they exist, to be stable only if they are continuously replenished and therefore likely to be associated with "venting or the presence of non-hydrous ices on the surface". Alternatively, if the surface is covered with non-volatiles and/or water ice, the atmospheric pressure would be very low and controlled by sputtering due to the impact of magnetospheric plasma and energetic particles on the surface[9]. In any case, the interaction with the magnetosphere is likely to be 'weak' as it is for Mercury[10], that is, the magnetic field and plasma sweep into and past the satellite being affected mainly by the additional inertia of newly formed ions (provided the satellite is non-conducting and non-magnetic). We substantiate these arguments here using the recent Voyager observations, and suggest that the interaction between Io and the magnetosphere can be understood if the atmosphere of Io were largely exospheric in nature and controlled by the vapour pressure of SO_2 ice which covers the surface.

The discovery of volcanic activity on Io by Voyager 1 (ref. 11) confirms that venting of gas from beneath the surface must be an important source of gas in the atmosphere. By analogy with the gaseous products of terrestrial volcanoes (ignoring the H_2O and N_2 which probably have an external origin) one might expect CO_2 and SO_2 to predominate together with smaller amounts of SO_3, H_2S, CO, A, He, H_2 and Cl_2 (ref. 12). The behaviour of such volatiles, if ejected from the volcanoes on Io, can be studied in terms of a vapour pressure versus temperature diagram as shown in Fig. 1. Evidently CO_2 and several other possible constituents such as CH_4, CO and N_2 have such high vapour pressures that they would tend to completely dominate the atmosphere if they were present in the volcanic ejecta in any significant amounts. However, Voyager 1 observations of energetic heavy ions in the jovian magnetosphere indicate that S and O ions are dominant and C and N ions (other than those of obviously solar origin) are essentially absent[8]. Furthermore, SO_2^+ ions and their dissociation products were detected by the plasma experiment[13] and an SO_2 absorption feature was identified on the surface of the satellite by the IR and radiometry experiments[14]. Accordingly, we conclude that the gaseous emission from the Io volcanoes is almost entirely SO_2 and that the other components commonly found in terrestrial volcanoes are absent or very depleted.

To understand how this would affect the atmosphere of Io we should consider the situation where the surface of the satellite is uniformly covered with SO_2 frost and the atmospheric pressure is determined locally by the surface temperature (the effects of