Hydrogen Ionization in the Shock Layer for Entry into the Outer Planets

JOHN T. HOWE*
NASA Ames Research Center, Moffett Field, Calif.

Nomenclature

c_i = mass fraction of species i
$\hat{c}_{p_i}$ = specific heat of species i, erg/mole°K
h = static enthalpy, cm^2/sec^2
H_2 = hydrogen concentration, mole/cm^3
l_{ion} = ionization length, cm
M_i = molecular weight of species i, g/mole
p = pressure, dynes/cm^2
R = universal gas constant, erg/mole°K
T = temperature, °K
U = probe velocity, cm/sec
v = velocity component normal to the shock behind the shock, cm/sec
X = mole fraction
x = distance behind the shock, cm
δ = shock standoff distance, cm
ε = density ratio across the shock, ρ_∞/ρ_s
θ = angle between flight velocity and the normal to the shock
ρ = density, g/cm^3
τ = time, sec

Subscripts
f = pertains to the flow
i = species i
ion = pertains to ionization process
s = conditions behind the shock wave
∞ = conditions ahead of the shock wave

EXPERIMENTS[1,2] have indicated that hydrogen ionization relaxation in hydrogen-helium mixtures may be sufficiently slow that the gascap on a probe entering the atmospheres of the outer planets may have a significant layer of nonequilibrium hydrogen atoms, hydrogen ions, and electrons. This atom-rich, electron-deficient layer would tend to reduce the radiative transfer incident on the heatshield of the entry probe. However, the presence of such a layer in the flowfield greatly complicates computations of the shocklayer environment, especially if finite rate chemistry must be included. This Note will try to assess, in an approximate way, the chemical state of the shock layer with respect to the reaction

$$H \rightarrow H^+ + e^- \tag{1}$$

for representative entries into Saturn, Uranus, and Jupiter.

For a given atmospheric composition and set of flight conditions, the ionization distance or relaxation time may be obtained from experimental data and may be compared with the residence time in the shock layer. In the stagnation region, the flow time required for a particle to move a distance x normal to the shockwave is

$$\tau_f = \int_0^x \frac{dx}{v} \tag{2}$$

Studies[3,4] of chemical and ionization relaxation behind strong shock waves indicate that pressure and enthalpy are almost constant in the relaxation zone and that density and velocity may vary by a factor of two, which is still of the order unity. Thus, for the present estimate, we let the velocity normal to the shock be constant at its value behind the shock

$$v \approx v_s = U\varepsilon\cos\theta \tag{3}$$

so that Eq. (2) becomes

$$\tau_f = x/\varepsilon U\cos\theta \tag{4}$$

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* Research Scientist. Member AIAA.

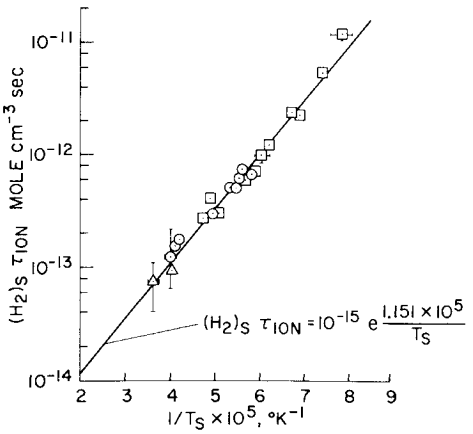

Fig. 1 Correlation of ionization data; 20.8% H_2, 79.2% He.

We represent the data of Fig. 1 for 20.8% H_2 and 79.2% He (taken from Fig. 7 of Ref. 1) by the line (on the log plot)

$$(H_2)_s\tau_{ion} = 10^{-15}\exp(1.151\times10^5/T_s)\ \text{mole sec/cm}^3 \tag{5}$$

where

$$(H_2)_s = (X_{H_2}p/RT)_s \tag{6}$$

then

$$\frac{\tau_{ion}}{\tau_f} = \frac{10^{-15}\varepsilon URT_s\cos\theta\exp(1.151\times10^5/T_s)}{X_{H_{2_s}}p_s\delta} \tag{7}$$

Conservation of energy and momentum across the shock yield, respectively,

$$h_s - h_\infty = U^2(1-\varepsilon^2)\cos^2\theta_s/2 \tag{8}$$

and

$$p_s = \rho_\infty U^2(1-\varepsilon)\cos^2\theta_s = \rho_s RT_s\left(\sum\frac{c_i}{M_i}\right)_s \tag{9}$$

where the last equality is the equation of state. From the definition of enthalpy, for no dissociation across the shock, with the specific heat fully excited rotationally and vibrationally, and with $T_\infty \ll T_s$, Eq. (8) becomes

$$T_s = U^2(1-\varepsilon^2)\cos^2\theta_s/2(\sum c_i\hat{c}_{p_i}/M_i)_s \tag{10}$$

The right-hand equality of Eq. (9) yields

$$T_s = \frac{\varepsilon(1-\varepsilon)U^2\cos^2\theta_s}{R\Sigma(c_i/M_i)_s} \tag{11}$$

A combination of Eqs. (10) and (11) with the equation of state yields the density ratio across the shock

$$\varepsilon = \left(2\sum X_i\frac{\hat{c}_{p_i}}{R} - 1\right)_s^{-1} \tag{12}$$

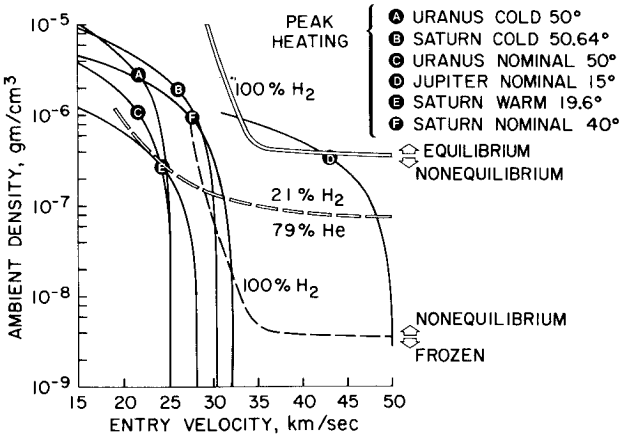

Fig. 2 Chemical state of the shock layer; $H \rightarrow H^+ + e^-$ reaction.

Table 1 Chemical state summary

	$(H \rightarrow H^+ + e^-)$ Stagnation region	Cone flank
Uranus (warm, nominal)	frozen	frozen
Uranus (cool)	equilibrium	equilibrium
Saturn (warm)	frozen	frozen
Saturn (nominal)	nonequilibrium	equilibrium
Saturn (cool)	~ equilibrium	equilibrium
Jupiter	equilibrium	equilibrium

For a binary mixture of molecular hydrogen and helium, Eq. (11) may be expressed as

$$T_s = \varepsilon(1-\varepsilon)(X_2 M_2 + X_1 M_1)_s U^2 \cos^2\theta_s / R \tag{13}$$

and Eq. (7) becomes

$$\frac{\tau_{\text{ion}}}{\tau_f} = \frac{10^{-15}(X_2 M_2 + X_1 M_1)_s U \cos\theta \exp(1.151 \times 10^5 / T_s)}{\rho_\infty \delta X_{H_{2_s}} \left(2\sum X_i \frac{\hat{c}_{p_i}}{R} - 1\right)_s^2} \tag{14}$$

For H_2 and He, $\hat{c}_{p_i}/R$ is 4.5 and 2.5, respectively, and, as noted, X_1 and X_2 are 0.208 and 0.792. For a standoff distance of 1 cm at the stagnation point, the locus of $\tau_{\text{ion}}/\tau_f = 0.1$ is shown as a function of flight conditions ρ_∞ and U in Fig. 2 by the double dashed line. Equilibrium exists above the line for that mixture.

For 100% H_2, we use the result of Fig. 9 of Ref. 1 and note that

$$l_{\text{ion}} = \varepsilon U \tau_{\text{ion}} \tag{15}$$

and from Eq. (4) we obtain

$$\frac{\tau_{\text{ion}}}{\tau_f} = \frac{\varepsilon U l_{\text{ion}} \cos\theta}{\varepsilon U x} = \frac{(\rho_\infty l_{\text{ion}})\cos\theta}{\rho_\infty x} = \left(\frac{p_\infty l_{\text{ion}} M_\infty}{R T_\infty}\right)\frac{\cos\theta}{\rho_\infty x} \tag{16}$$

Although the data are given as $p_\infty l_{\text{ion}}$ as a function of U, the important parameter is $\rho_\infty l_{\text{ion}}$, which is obtained from Eq. (16) for $T_\infty = 300°$K. Accordingly, the loci of $\tau_{\text{ion}}/\tau_f = 0.1$ and 10.0 are shown in Fig. 2 by the double solid curve and the single dashed curve, respectively, as a function of the flight conditions ρ_∞ and U, again for a standoff distance of 1 cm. Chemical equilibrium exists above the upper curve, nonequilibrium between the two, and, essentially, frozen flow below the lower curve for pure H_2.

Some representative entry trajectories for Saturn, Uranus, and Jupiter are also plotted on the figure. Peak heating is shown by the lettered solid symbol in each case. For Jupiter, the atmospheric composition is approximately 85% H_2, 15% He, and the equilibrium line probably lies somewhat below the symbol D; that is, for the highly energetic Jupiter entry, the ionization relaxation would be complete before the point of maximum heating. At the other extreme, for the nominal Uranus atmosphere (95% H_2, 4% He),[5] curve C indicates that the reaction (1) would be frozen.

A summary of these estimates for entry into the various model atmospheres of the outer planets is shown in Table 1 for both the stagnation region and for the flank of a 60° half-angle cone having a 1-m ray. Interestingly, finite rate chemistry seems to play a role only for entry into the Saturn nominal atmosphere (79% H_2, 20% He) at a fairly steep entry angle (40°). For shallow entry (15°) into that atmosphere, the reaction (1) would probably be frozen. Thus, except for the steep entry into the Saturn nominal atmosphere, the computation of all entry probe gascaps for the outer planets can probably be considered on either a frozen or a chemical equilibrium basis and avoid the complications of finite rate chemistry.

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Role of Plasma Boundary Conditions in the Comparison of Electron Plasma Temperatures

A. SINGER* AND J. M. MINKOWSKI†

The Johns Hopkins University, Baltimore, Md., and Harry Diamond Laboratories, Washington, D.C.

Introduction

THE first two attempts[1,2] to determine the electron temperature of shock-heated plasma by microwave techniques yielded results that cannot be meaningfully compared with the values predicted by shock-wave theory, either because insufficient plasma parameters were measured[1] or because there is considerable doubt as to whether the plasma was in thermal equilibrium.[2] Avoiding these pitfalls, Aro and Walsh[3] obtained values for electron temperature of shock-heated argon (initially at 4 torr and room temperature) over a very large electron density range, 10^{16}–10^{22} m^{-3}, corresponding to shock levels of Mach 6.8–10.5, by means of a set of microwave horns and an associated superheterodyne receiver centered at 9.05 GHz. However, a prominent feature of the Aro-Walsh experiment was that the results significantly exceeded the theoretically predicted values in three Mach regions: below Mach 7.4, between Mach 8.0 and 8.8, and above Mach 9.7, corresponding to electron densities, n_e, below 4×10^{18}, between 5×10^{19} and 6×10^{20}, and above 4×10^{21} m^{-3}. This was particularly puzzling because no plausible physical mechanism could be found to account for this anomaly. In order to check whether these results were genuine, Aro and Walsh performed another experiment in which they viewed the same plasma in a waveguide probe.[4] Since the waveguide probe results were in much closer agreement with theory and almost consistently lower than the theoretical values, they concluded that the anomalies were due to a plasma boundary layer associated with the aerial geometry of the microwave-horn experiment.

It has been recently shown,[5] however, that in the upper Mach region (above 9.7) the anomaly was only apparent and was in

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* Research Associates, Department of Electrical Engineering; also Research Engineer, Harry Diamond Laboratories.

† Associate Professor, Department of Electrical Engineering.