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# THE ROLE OF PLASMA PROCESSES IN THE SPACE SHUTTLE ENVIRONMENT

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**Abstract**—Sources of enhanced ionization in the Space Shuttle environment are considered, with particular emphasis on the plausibility of a plasma discharge resulting from the Critical Ionization Velocity (CIV) mechanism. These sources are then compared with ion loss processes. It is found that within the shuttle environment the loss of ions is faster than ion production from CIV, leading to the conclusion that the observed enhancement in ionization arises from sources other than plasma interactions. It is suggested that the seemingly anomalous ionization levels can be attributed to firings of thrusters of the attitude control system. In addition, the connection between the shuttle glow phenomenon and the enhanced ionization is considered and found to be circumstantial and not causal, thereby strengthening the argument that the primary source of the shuttle glow is chemical interactions of atmospheric gases with surfaces or with surface-adsorbed gases.

## INTRODUCTION

Measurements of the environment near the Space Shuttle have indicated the presence of two unexpected phenomena: the shuttle glow (Banks *et al.*, 1983; Mende *et al.*, 1983) and regions of enhanced ionization (Shawhan and Murphy, 1983; McMahon *et al.*, 1983; Siskind *et al.*, 1984; Raitt *et al.*, 1984; Shawhan *et al.*, 1984). A number of theories have been proposed to explain the origin of the shuttle glow. These theories and the shuttle glow phenomenon have been reviewed in several recent publications (Green *et al.*, 1985; Mende and Swenson, 1985; Kofsky and Barrett, 1986; Murad, 1987a, b). All but one of the theories have invoked traditional chemical reactions, either gas phase or gas–surface reactions, which did not depend on the charged particle background. The one exception has been the plasma theory of Papadopoulos (1984), which has made an association between the shuttle glow phenomenon and reports of enhanced ionization in the shuttle environment. In making that association, Papadopoulos (1984) invoked the Critical Ionization Velocity (CIV) mechanism as a source of the enhanced ionization, a consequence of which would be the excitation of ions to upper electronic states. These excited molecular and atomic ions would subsequently radiatively de-excite in the atmosphere about the shuttle. On the other hand, the most likely chemical explanation for the origin of the glow is the excitation of $NO_2$ by the surface-catalyzed recombination of O and NO on shuttle surfaces (Swenson *et al.*, 1985). Supporting this idea are the mass spectrometer data from the *Dynamic Explorer* satellite (Engebretsen and Hedin, 1986) and from the Space Shuttle (von Zahn and Murad, 1986) which suggest that, indeed, $NO_2$ is present in sufficient quantities to be consistent with this mechanism.

We explore in this report the causal connection between the observations of enhanced ionization and the shuttle glow and examine in more detail the applicability of the CIV hypothesis as a source of enhanced ionization in the shuttle environment. Although others have questioned the connection from an observational standpoint (Kofsky, 1984; Yee *et al.*, 1984; Slanger, 1986), we consider here the fundamental processes which sustain and drive CIV discharges, and examine the likelihood of its occurrence on the shuttle. The CIV theory, which was used by Papadopoulos, was first suggested by Alfvén (1954) as the cornerstone of his theory for the formation of the solar system. The basis of his argument was that a neutral gas, travelling transverse to a magnetized plasma at a relative velocity $v \geq$ a critical velocity $v^*$, is ionized. $v^*$ is given by $13.9\sqrt{(IP/M)}$, where 13.9 is a conversion constant, $IP$ is the ionization potential of the neutral atom in electronvolts, and $M$ the mass in amu. A series of laboratory experiments using homopolar devices (Alfvén, 1960; Fahleson, 1961) and neutral beams

(Danielsson, 1970, 1973) have provided strong evidence for the existence of CIV. Reviews of the experimental evidence and of the theory have recently been published by Danielsson (1973) and Newell (1985), respectively.

This report is divided into several sections which detail the requirements for the discharge to proceed within the finite geometry of the shuttle and in the presence of plasma loss processes. An alternate mechanism which could explain the observations of disturbed plasma regions near the shuttle in the absence of CIV is proposed. Finally, an estimate of the glow intensity which is based solely on reported measurements of the disturbed regions is compared to the measured intensity of the glow and discussed.

## DISCUSSION

### (A) *Plasma considerations*

(i) *Electron impact ionization times.* It is implicit in the CIV theory that ionization is initiated and propagated by electron impact. Since the energy distribution of electrons in the ionosphere is thermal in nature, their energies are below the ionization potential of all the elements. Thus, it is necessary to generate high energy tails if enhanced ionization is to occur in the vicinity of the shuttle. The results reported by McMahon *et al.* (1983) indicate that there is an enhancement in electron densities for electrons in the range 20–100 eV. We consider here the case of an electron having an average energy of 50 eV, at which value the electron impact ionization cross-section is about 1(−17)† cm$^2$ for gaseous species such as $N_2$, although for metals it can be appreciably higher (Märk, 1985). The ionization time, $\tau_i$, is given by:

$$\tau_i = 1/[N \cdot \sigma(E) \cdot V(E)] \tag{1}$$

where $N$ is the neutral density, $\sigma(E)$ the electron impact ionization cross-section as a function of energy, and $V$ the velocity of a hot electron. For a neutral concentration of ~ 1(10) cm$^{-3}$ [corresponding to a pressure of 3(−7) torr], $\sigma(E)$ of 1(−17) cm$^2$, and a velocity of 1(8) cm s$^{-1}$, the ionization time turns out to be about 0.1 s, thereby placing an upper limit on the time scale of the loss mechanisms. If the losses occur at shorter times, then the discharge can not be sustained.

(ii) *Townsend's criterion.* In order for the CIV mechanism to proceed, there must exist a "seed" density of energetic electrons within the discharge region capable of ionizing the background gas. The Townsend criterion stipulates that in order to sustain a discharge, there must be on average at least one electron impact ionization during the lifetime, $\tau$, of an electron within the discharge region. This implies that an electron heated by a plasma process (as yet undefined) has to have enough time to ionize another neutral atom or molecule during its transit.

Within the theory of quasilinear plasma physics (Formisano *et al.*, 1982), it is calculated that thermal electrons can absorb electrostatic wave energy to form a high energy tail or plateau in their energy distribution. The formation of this hot tail, rather than bulk electron heating, renders the heated electrons energetic enough to cause ionization of the neutral gas. Only a small fraction, $\alpha$, of the total population of electrons migrates into the tail, while the bulk of the electron population is essentially unheated, as illustrated in Fig. 1. The unheated electrons, in contrast to those in the tail, have insufficient energy to ionize the neutral gas. Consequently, the Townsend criterion needs to be modified so that a heated electron has to make at least $\alpha^{-1}$ ionizations during its lifetime, $\tau_L$, within the discharge region. Mathematically, the modified Townsend criterion becomes:

$$\alpha^{-1}[\tau_i + \tau_H] < \tau_L \tag{2}$$

where $\tau_i$ is the ionization time, and $L$ is the transverse dimension of the discharge region. The time, $\tau_L$, of a heated electron in the discharge region is given by:

$$\tau_L = L/V. \tag{3}$$

Tanaka and Papadopoulos (1982) obtained the following expression for the electron heating time:

$$\tau_H \sim 30/\omega_{LH} \tag{4}$$

where $\omega_{LH}$ is the lower hybrid frequency.

In the shuttle environment, equation (4) typically yields $\tau_H \sim$ 1–10 ms, depending on the ion mass and the local magnetic field strength. To calculate the inequality in equation (2), we use the following typical

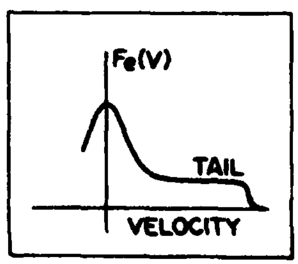


FIG. 1. ELECTRON ENERGY DISTRIBUTION RESULTING FROM HEATING BY A PLASMA PROCESS.

† Throughout this paper, $a(b)$ denotes $a \times 10^b$.

parameters: $\langle E \rangle \approx 5$–$30$ eV (Papadopoulos, 1984), $L \sim 6$ m, and $\alpha \sim 0.01$, $N \sim 1(10)$ cm$^{-3}$, and $\sigma \sim 0.5(-16)$ cm$^2$. As a result inequality (2) gives about 2 s on the left side and about 6 $\mu$s on the right; the two sides differ by orders of magnitude. Thus Townsend's criterion renders a sustained discharge unlikely in this environment.

In order to examine the parametric dependence of the modified Townsend criterion, equation (2), it is convenient to define a ratio $F$:

$$F(N, V, L) = \alpha^{-1}(\tau_i + \tau_H)/\tau_L. \tag{5}$$

When $F(N) \leqslant 1$, equation (2) would be satisfied. Figure 2 shows the dependence of $F(N)$ on the neutral density, $N$, for various values of $V$ starting from that of ion sound velocity [$V \sim C_s \sim 1(5)$ cm s$^{-1}$; Papadopoulos, 1984], while the parameter $L$ is taken as 6 m. $F(N)$ is a monotonically-decreasing function, because the probability of ionization increases as $N$ increases. The slope of $F(N)$ decreases to zero asymptotically, because at high $N$ $\tau_i$ becomes short compared to the heating time, $\tau_H$, so that the latter gradually becomes dominant. As a function of spatial dimension, $L$, ln $F(L)$ decreases linearly with ln $L$ (Fig. 3). In this figure, $F(L)$ is plotted with $N \sim 1(10)$ cm$^{-3}$ (Narcisi *et al.*, 1983) and the same value of $V$ as in Fig. 2. $F(L)$ is greater than unity until $L$ becomes quite large. This implies that CIV discharge can be sustained only when $L$ is very large (perhaps $\sim 1$ km). The shuttle tail is only 6 m. Since the energy range of a hot electron tail in the shuttle vicinity is estimated to be 5–30 eV (Papadopoulos, 1984) the velocity $V$ of a hot electron traversing a discharge region is expected to be much greater than $C_s$. With these parametric values we conclude that $F \gg 1$. A higher neutral density, for example $1(11)$ cm$^{-3}$, would not change the conclusion. Therefore a discharge in the shuttle environment is highly unlikely.

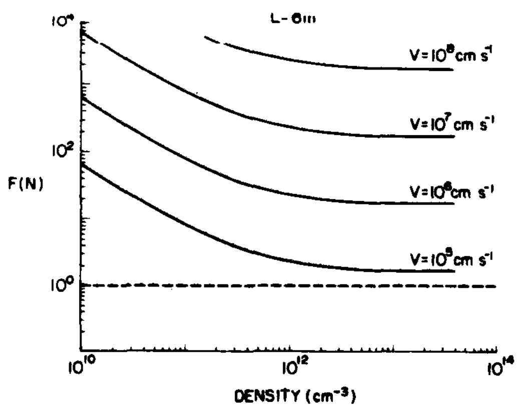


FIG. 2. VARIATION OF $F$ (SEE TEXT FOR DEFINITION) AS A FUNCTION OF NEUTRAL NUMBER DENSITY.

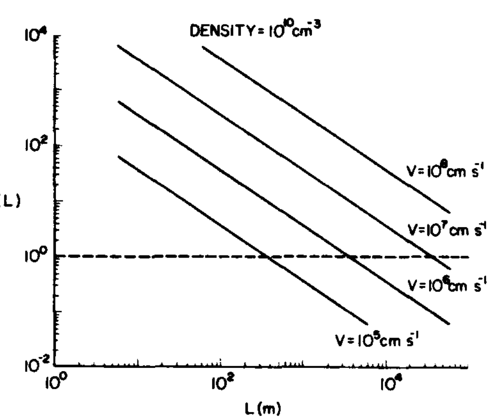


FIG. 3. VARIATION OF $F$ AS A FUNCTION OF CONFINEMENT LENGTH.
See text.

(iii) *The wave vector triangle*. The relevance of the lower hybrid (LH) wave heating of electrons to the CIV process has been studied by several authors (Raadu, 1978; Galeev, 1981; Formisano *et al.*, 1982; Papadopoulos, 1984, 1985; Abe and Machida, 1985; Machida and Goertz, 1986). Basic investigations of the LH wave electron heating have been performed by McBride *et al.* (1972). McBride *et al.* (1972) and Papadopoulos (1984) have calculated that the maximum efficiency of heating occurs at the wave vector angle $\theta = 1$, where $\theta$ is given by:

$$\theta = (k_z/k)(M/m)^{1/2}. \tag{6}$$

The wave vector $k$ is related to the wavelength, $\lambda$, and to the hybrid frequency, $\omega_{LH}$, by:

$$k = 2\pi/\lambda \tag{7}$$

$$k = \omega_{LH}/v \tag{8}$$

where $v$ is the beam velocity of the ions energizing the waves.

$\theta = 1$ leads to a requirement that the size of the wave vector triangle (Fig. 4) be:

$$k_z^{-1} \sim (1/k)(M/m)^{1/2}. \tag{9}$$

The size requirement for CIV in space has been discussed by Newell (1985) and Kelley *et al.* (1986) in connection with the seemingly different observed efficiencies for CIV in the laboratory (high efficiency) and in space (low efficiency). We examine below the size requirement [equation (9)] for the case of homopolar devices and for the case of space experiments. From equation (4) and taking the electron heating time, $\tau_H$, to be 3 $\mu$s (Fahleson, 1962) we obtain:

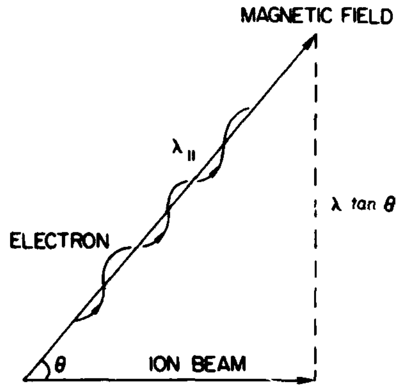


FIG. 4. WAVE VECTOR TRIANGLE.

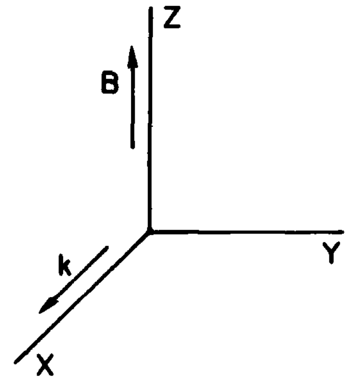


FIG. 5a. COORDINATES FOR A SIMPLE MODEL OF A FINITE-SIZED BEAM PROPAGATING ALONG THE $k$-DIRECTION PERPENDICULAR TO THE AMBIENT MAGNETIC FIELD $B$, WHICH IS IN THE $z$-DIRECTION.

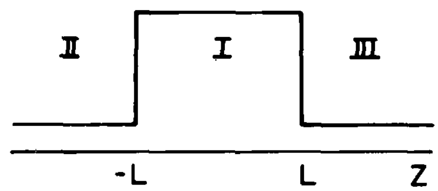


FIG. 5b. A SIMPLE DENSITY PROFILE.

$$\omega_{LH} \sim 1(4) \text{ kHz}. \quad (10)$$

Substituting this value of $\omega_{LH}$ into equation (9), and assuming $v \sim 37$ km s$^{-1}$ for $H_2$ (Fahleson, 1962), we obtain $\lambda \sim 14$ cm, which is smaller than the dimensions of a homopolar device (Fahleson, 1962, gives dimensions of 15 cm height × 20 cm radius).

For the Space Shuttle conditions, substituting $\omega_{LH} \sim 3.6$ kHz (Kelley *et al.*, 1986) and $v \sim 2\times 7.3$ km s$^{-1}$, we obtain $\lambda \sim 1$ km, which agrees with Kelley *et al.* (1986). This is about two orders of magnitude larger than the Space Shuttle tail cross-section. In other words, the wave vector triangle does not fit into the transverse direction of the ion beam.

(iv) *Wave vector condition for a finite system.* We consider here the case of a system with finite dimensions having a simple configuration as shown in Fig. 5a: the ambient magnetic field $B$ is parallel to the $z$-axis and the ion beam parallel to the $x$-direction. The stability analysis seeks a solution of the form

$$\varphi = \varphi(z)\exp(-i\omega t + ikx) \quad (11)$$

resulting in an eigenvalue problem of the form (see Appendix)

$$(d/dz)\{\varepsilon_z(z)[d\varphi(z)/dz]\} + T^2\varphi(z) = 0 \quad (12)$$

where

$$T^2 = -k^2\varepsilon_x(k,\omega), \quad (13)$$

$\varphi$ is the plasma wave potential, $k$ the wave vector ($\equiv k_x$ in this geometry), $\omega$ the wave frequency, and $\varepsilon$ the dielectric function.

The eigenvalue equation, (13), can be solved for given simple density profiles. We consider a square density profile (Fig. 5b), in which the plasma densities are $n$ inside the beam (Region I) and $n_0$ outside the beam (Regions II and III), while the boundaries of the beam are $z = \pm L$. For this case equation (12) reduces to (see Appendix)

$$d^2\varphi/dz^2 - \Gamma^2\varphi = 0 \quad (14)$$

where

$$\Gamma^2(k,\omega) = k^2\varepsilon_x(k,\omega)/\varepsilon_z(k,\omega). \quad (15)$$

The appropriate boundary conditions are $\varphi$ being finite at infinity and $\varphi$ as well as $d\varphi/dz$ being continuous at the beam boundaries. Aside from the trivial solution $\varphi = 0$, we obtain, as shown in the Appendix, the condition

$$\Gamma\tanh(\Gamma L) = -\Gamma_0 \quad (16)$$

where $\Gamma_0$ is the function $\Gamma$ in Region II (or III), where the density is $n_0$. Using this simple density profile we have solved equation (16) numerically; the model assumes a finite $k_\perp$ and no $k_\parallel$ [see equations (A1) and (A2) in the Appendix]. Numerical results are shown in Figs. 6a and 6b. In the infinite beam limit ($kL \to \infty$), the maximum growth rate ($\mathrm{Im}\,\omega/\omega_i \sim 0.19$) occurs at $kv/\omega_i \sim 0.8$ (Fig. 6a). Figure 6b shows the finite beam case where the growth rate ($\mathrm{Im}\,\omega/\omega_i$) at $kv/\omega_i \sim 0.8$ is plotted as a function of $kL$; $\mathrm{Im}\,\omega/\omega_i$ reaches an asymptotic value of 0.19 as $kL \to \infty$, which agrees with the infinite beam result in Fig. 6a. It is interesting to observe that in Fig. 6b the instability growth rate, $\mathrm{Im}\,\omega/\omega_i$, decreases with

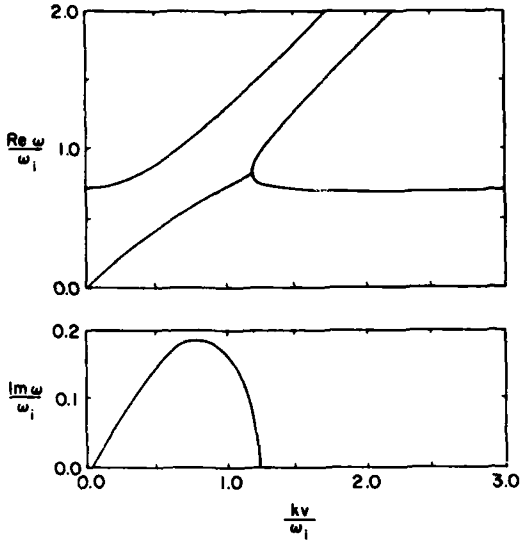


FIG. 6a. DISPERSION RELATION OF A SIMPLE MODEL OF AN INFINITE BEAM PROPAGATING PERPENDICULAR TO THE AMBIENT MAGNETIC FIELD.

The imaginary root $\mathrm{Im}\,\omega$ corresponds to the $\mathrm{Re}\,\omega$ branch that starts at $\omega = 0$. Max $[\mathrm{Im}\,\omega/\omega_i] \sim 0.19$ occurs at about $kv/\omega_i \sim 0.8$. The parameters used are $\Omega_e/\omega_e = 1$, and $n_b/n_0 = 0.1$. The ions are $O_2^+$.

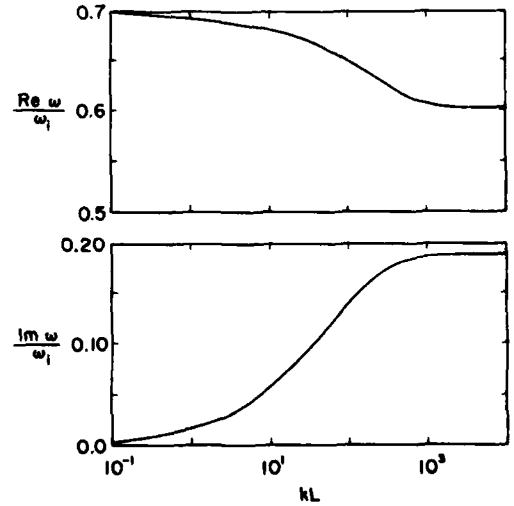


FIG. 6b. NUMERICAL SOLUTIONS OF EQUATION (16) AS FUNCTIONS OF FINITE $kL$.

The parameters used are the same as in Fig. 6a, with $kv/\omega_i = 0.8$. Notice that the growth rate, $\mathrm{Im}\,\omega/\omega_i$, decreases as $kL$ decreases, and that in the $kL \to \infty$ limit, one recovers the maximum growth rate $\mathrm{Im}\,\omega/\omega_i \sim 0.19$, agreeing with the results in Fig. 6a.

decreasing $kL$. For example, taking a shuttle tail dimension of $2L \sim 6$ m and a wavelength, $\lambda$, $\sim 6$ m (i.e. $kL \sim \pi$), the instability growth rate is reduced to $\sim 1/5$ of that in the infinite plasma case. For longer wavelengths, the growth rate would be even lower. This result suggests that long wavelength plasma instabilities obtained using infinite plasma theories may be rendered inappropriate (i.e. inefficient) by the finite spatial extent of the surfaces.

**(B)** *Ion loss mechanism*

(i) *Diffusion*. Ionization generated by the CIV process in the vicinity of the Space Shuttle can be lost by diffusion. If the diffusion time is shorter than the ionization time, then the plasma density cannot be increased. Parallel to a magnetic field, diffusion of a plasma with a neutral gas background is governed by the ambipolar diffusion process. The ambipolar diffusion coefficient, $D_a$, is $\sim 2D_i$, where $D_i$ is given by:

$$D_i = kT_i/M\nu = kT_e/[M \cdot N \cdot \sigma_{in} \cdot v] \qquad (17)$$

where $M$, $N$, $v$, and $\sigma_{in}$ are the ion mass, number density, velocity, and ion–neutral collision cross-section, respectively. Across a magnetic field, $B$, diffusion of a plasma is given, approximately, by Bohm's semi-empirical formula (Chen, 1974):

$$D_b = kT_e/(16 \cdot e \cdot B). \qquad (18)$$

In order to estimate the magnitude of this loss process, we consider the case where $kT_e \approx 30$ eV, $B \approx 0.3$ G, $M = 16$, and $\sigma_{in} \approx 1(-15)$ cm$^2$ (Hamilton and Knewstubb, 1984). The scale length is taken as 6 m, which is approximately the length of the shuttle tail as well as the gyroradius of an ion with about the shuttle speed. For a simple cylindrical geometry, the diffusion time, $\tau_d = R^2/(2D)$, where (Chen, 1974):

$$D = D_a + D_B. \qquad (19)$$

Figure 7 shows the competition between diffusion time and electron impact ionization time. If we equate $\tau_i$ to $\tau_d$, we obtain a critical value for $N$, $N_c$ (the crossing point in Fig. 7), above which ionization dominates over diffusion, and below which diffusion dominates. This value of $N_c$ turns out to be $\sim 5(9)$ cm$^{-3}$.

(ii) *Dissociative electron–ion recombination*. Once CIV has occurred, the discharge will be quenched if the electron and ion densities exceed a value whose magnitude depends on the recombination coefficient. Radiative recombination of atomic ions:

$$A^+ + e \to A + h\nu \qquad (20)$$

where $A$ is an atomic ion, is exceedingly slow, $k_{20}$ being $\sim 4(-12)$ cm$^3$ molec$^{-1}$ s$^{-1}$ (Bates and Dalgarno, 1962; Dunn *et al.*, 1984). However, the rate coefficient

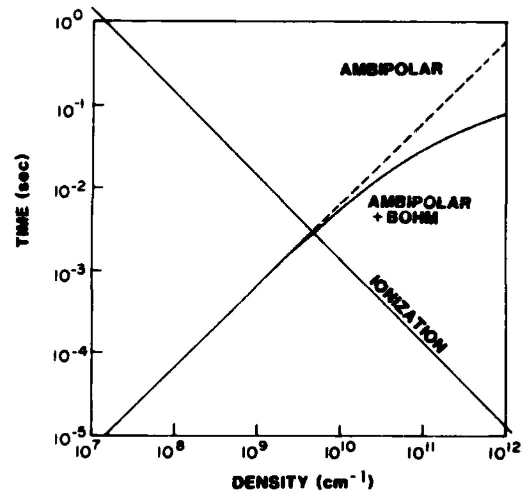


FIG. 7. COMPETITION BETWEEN IONIZATION AND DIFFUSION TIMES.

for dissociative recombination:

$$AB^+ + e \rightarrow A + B \tag{21}$$

where $AB$ is a generic molecular ion, is much larger, $k_{21}$ being of the order of $1(-6)$ to $1(-7)$ $cm^3$ $molec^{-1}$ $s^{-1}$ (Bates, 1979; McGowan and Mitchell, 1984). The increased pressure near the shuttle is due to molecular contaminants such as $H_2O$ and $CO_2$ (Wulf and von Zahn, 1986), and measurements suggest that ions from these molecules (Narcisi *et al.*, 1983; Grebowsky *et al.*, 1988) are the primary sources of enhanced ionization. Loss by electron–ion recombination would involve these contaminants, as discussed recently (Murad and Lai, 1986). Briefly, there are three immediate consequences of this loss mechanism: (1) the density of electrons, crucial in sustaining the chain ionization process, is reduced by recombination; (2) considerable energy loss by hot electrons is lost as a result of radiation liberated in reaction (21); and (3) a lowering of the mass of the neutral species would result in a corresponding increase of the critical velocity threshold discussed earlier (Axnäs, 1978). Depending on the parametric conditions, CIV may proceed in an oscillatory manner, or it may be completely quenched (Lai *et al.*, work in progress). If the relative velocity between the neutral gas and the plasma is not high enough to replenish the losses, the discharge process would be quenched. In the case of the Space Shuttle, the energy budget of CIV is already marginal; it relies on the 8% ambient ions (Papadopoulos, 1983, 1984) reflected on the ram side of the Space Shuttle. Any loss mechanism would make the initiation of the CIV discharge even more difficult.

(iii) *Line excitation*. Neutral species can be excited to allowed electronic states by electron bombardment, which would, in turn, radiate very fast (within a few nanoseconds). The net effect of such a process is to cool the electrons; Newell and Torbert (1985) have calculated that nearly 50% of the electron energy is lost in neutral heating in the shuttle environment. This becomes a substantial loss mechanism which would adversely affect an already-marginal CIV energy budget, as discussed above. A loss of 50% of the energy would tend to quench the nascent discharge. A more detailed study of neutral excitation and de-excitation processes in molecular CIV systems is in progress (Murad, 1987a; Lai *et al.*, 1988).

## CONCLUSIONS

### (A) *Ionization*

The origin of the observed enhancement in ionization in the vicinity of the Space Shuttle is problematic, since, as discussed above, CIV is unlikely to be sustained in the vicinity of the Space Shuttle. This conclusion then requires an alternative explanation for the origin of ionization in the vicinity of the Space Shuttle. A likely source is from thruster firings, since mass spectrometric measurements in the bay of the Space Shuttle indicate a direct correlation between densities of ions (Narcisi *et al.*, 1983; Grebowsky *et al.*, 1987) and neutrals (Narcisi *et al.*, 1983; Wulf and von Zahn, 1986) with thruster firings. While the flow fields from thrusters to the shuttle bay are not known at this time, it seems reasonable to attribute the observed enhancement in ionization level to large amounts of ions released in the exhaust of thruster engines.

### (B) *Glow*

Mende and Swenson (1985) have estimated the glow intensity to be 10–100 kR [1 R = 1(6) photons $cm^{-2}$ $s^{1}$]. This corresponds to a photon emission rate of 1(10)–1(11) photons $cm^{-2}$ $s^{-1}$ per column length, this being the length of the tail section of the Space Shuttle (about 6 m). In the plasma mechanism the ionization involves electron impact ionization and excitation to upper electronic states of the ions:

$$e_f + AB \rightarrow (AB^+)^* + 2e \tag{22}$$

$$(AB^+)^* \rightarrow AB^+ + h\nu. \tag{23}$$

$AB$ is any neutral species (atomic or molecular), $e_f$ a fast electron, and $(AB^+)^*$ an excited state of $AB^+$. The rate of formation of $(AB^+)^*$ is given by $\sigma_{22} \cdot V \cdot [e_f] \cdot [AB]$, where $\sigma_{22}$ is the cross-section for reaction 22; $V$ the velocity; $[e_f]$, the concentration of fast electrons; and $[AB]$ the concentration of the neutral species $AB$. For $CO_2$ at an electron energy of 150 eV, $\sigma_{22}$ is $\sim 0.5(-16)$ cm$^2$ (Mentall *et al.*, 1973). At 20–30 eV, $\sigma_{22}$ is likely to be much smaller; a conservative estimate would be $1(-17)$ cm$^2$. For $[e_f]$, we use a value of 2(5) cm$^{-3}$, as has been reported by McMahon *et al.* (1983), and for $[AB]$ we use a value of 1(10) cm$^{-3}$. Using $V \sim 1(8)$ cm s$^{-1}$, we calculate the rate of formation of $(AB^+)^*$ to be 2(7) cm$^{-3}$ s$^{-1}$. For a path length of 6 m, this density corresponds to a column density of 1.2(10) molecules cm$^{-2}$ s$^{-1}$. If the emission rate is high, e.g. 10%, then the predicted intensity would have a maximum of 1.2(9) photons cm$^{-2}$ s$^{-1}$, or 1 kR. This corresponds to 0.1–0.01 of the observed intensity. Thus we conclude that the plasma hypothesis cannot explain the shuttle glow phenomenon.

Yee *et al.* (1984) reached a similar conclusion based on the lack of correlation of shuttle glow intensity with plasma density. More recently, Slanger (1986) found a lack of correlation with neutral density in the V section of the tail. Moreover, the near-continuum nature of the glow (Swenson *et al.*, 1985) has lent credence to the suggestion that the glow is caused by $NO_2$ formed by recombination on the surfaces of the shuttle. Indeed, mass spectrometric data support this finding (von Zahn and Murad, 1986). The nature of the spectrum also argues against the plasma hypothesis, as discussed in some detail by Kofsky (1984). For example, the major contaminant on the Space Shuttle is $H_2O$. The spectrum of its ion, which would be formed in reaction (22), is a well defined band system (Lew, 1976) contrary to the observation.

### (C) *Limits on ionization*

Figure 7 shows a crossing between diffusion loss of ions and generation of ions by electron impact at a neutral density of $\sim 5 \times 10^9$ cm$^{-3}$. This corresponds to the density at an altitude of $\sim 240$ km (U.S. Standard Atmosphere, 1976). At altitudes greater than this ions will be lost by diffusion, while at lower altitudes, it is likely that ionization will dominate diffusion. At lower altitudes other loss mechanisms, such as electron-ion recombination, might become dominant.

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## APPENDIX

*Linear dispersion relation*

Consider an infinite slab beam with density $n$ and thickness $2L$ interacting with an infinite plasma density $n_0$ in the presence of a magnetic field $B$ ($\Omega = eB/mc$) in the $z$ direction, which is perpendicular to the beam propagating with velocity $v$ in the $x$ direction (see Fig. 5a). For electrostatic perturbations of the form

$$v_1 = v_1(z)\exp(-i\omega t + ikx) \tag{A1}$$

and

$$\varphi = \varphi(z)\exp(-i\omega t + ikx) \tag{A2}$$

the equation of motion

$$m(d\mathbf{v}_1/dt) = e[\mathbf{E}_1 + (1/c)(\mathbf{v}_1 \times \mathbf{B})], \tag{A3}$$

where $\mathbf{E}_1 = -\nabla\varphi$, and the continuity equation

$$\partial n_1/\partial t + \nabla\cdot(n_0\mathbf{v}_1 + n_1\mathbf{v}) = 0 \tag{A4}$$

yield

$$4\pi n_1 = \omega_e^2 k^2 \varphi/[(\omega - kv)^2 - \Omega^2] - (\partial/\partial z)[\omega_e^2(\partial\varphi/dz)]/[\omega - kv]^2 \tag{A5}$$

where the plasma frequency $\omega_e\ [\equiv \sqrt{(4\pi e^2 n/m)}]$ is a function of the density, $n(z)$. For self-consistency, the quantities $n_1$ and $\varphi$ have to satisfy Gauss's equation:

$$\nabla^2\varphi = -4\pi n_1. \tag{A6}$$

Eliminating $n_1$ from (A5) and (A6), one obtains

$$(d/dz)[\varepsilon_z(z)(d/dz)]\varphi(z) + T^2\varphi = 0 \tag{A7}$$

where

$$\varepsilon_z(z) = 1 - \omega_e^2/(\omega - kv)^2,$$

$$\varepsilon_x(z) = 1 - \omega_e^2/[(\omega - kv)^2 - \Omega^2], \quad \text{and}$$

$$T^2 = -k^2\varepsilon_x(z). \tag{A8}$$

To recover the infinite limit for

$$\varphi(z) \sim \varphi(0)\exp(-ik_z z) \quad (A9)$$

one obtains from (A7) and (A8) the dispersion relation

$$1-\omega_e^2/(\omega-k_x v)^2(k_z/k)^2 + \omega_e^2/[(\omega-k_x v)^2-\Omega^2](k_x/k)^2 = 0 \quad (A10)$$

where $k^2 = k_z^2+k_x^2$.

*Simple density profile*

The eigenvalue equation (A7) can be solved for a given density profile. For the simplest case of perpendicular beam propagation in a background plasma, we consider a square density profile, where the beam is propagating in the $x$-direction; the density profile along the $z$-direction is displayed in Fig. 5b. The plasma densities are assumed to be constant inside the beam (Region I) and outside the beam (Regions II and III). The beam boundaries are at $z = L$ and $-L$.

For this case of a square density profile, the plasma frequency $\omega_e$ is constant ($d\omega_e/dz = 0$) inside each region. Equation (A7) becomes

$$d^2\varphi(z)/dz - \Gamma^2\varphi(z) = 0 \quad (A11)$$

where

$$\Gamma^2 = k^2\varepsilon_x(z)/\varepsilon_z(z). \quad (A12)$$

The solution of equation (A11) now yields

$$\varphi(z) = a\,e^{-\Gamma z}+b\,e^{\Gamma z} \quad \text{Region I} \quad (A13)$$

and

$$\varphi(z) = a_0\,e^{-\Gamma_0 z}+b_0\,e^{\Gamma_0 z} \quad \text{Regions II and III.} \quad (A14)$$

Using the boundary conditions:

(1) $\varphi(\infty)$ is finite, and
(2) both $\varphi$ and $d\varphi/dz$ are continuous at $z = L, -L$

we obtain, aside from the trivial solution of constant potential which is not of interest, the following dispersion relation:

$$\Gamma\tanh(\Gamma L) = -\Gamma_0 \quad (A15)$$

where $\Gamma$, defined in (A12), is a function in the beam region I, while $\Gamma_0$ refers to regions II and III, which are outside the beam.

Taking into account both electron and ion contributions explicitly, (A12) becomes

$$\Gamma^2 = k^2\varepsilon_x(n_e,n_i,n_b)/\varepsilon_z(n_e,n_i,n_b) \quad (A16)$$

and

$$\Gamma_0^2 = k^2\varepsilon_x(n_e,n_i,0)/\varepsilon_z(n_e,n_i,0) \quad (A17)$$

where

$$\varepsilon_x(n_e,n_i,n_b) = 1-\omega_e^2/(\omega^2-\Omega_e^2) - \omega_i^2/\omega^2-\omega_b^2/[(\omega-kv)^2-\Omega_b^2] \quad (A18)$$

and

$$\varepsilon_z(n_e,n_i,n_b) = 1-\omega_e^2/\omega^2-\omega_i^2/\omega^2-\omega_b^2/(\omega-kv)^2. \quad (A19)$$

0 refers to the outside of the beam, $\omega_e$ is the background plasma frequency, $\omega_i$ the ion plasma frequency, $\Omega_e$ is the background gyrofrequency, $B$ the ambient magnetic field, $\omega_b(\omega_b^2 = 4\pi e^2 n_b/M)$ the ion beam plasma frequency, $n_b$ ($n_e = n_0+n_b$) the ion beam density, $\Omega_b$ the ion beam gyrofrequency, $v$ the ion beam velocity, and $k$ the wave vector. The dispersion relation (A15) is derived as described previously.

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Abstract—Sources of enhanced ionization in the Space Shuttle environment are considered, with particular emphasis on the plausibility of a plasma discharge resulting from the Critical Ionization Velocity (CIV) mechanism. These sources are then compared with ion loss processes. It is found that within the shuttle environment the loss of ions is faster than ion production from CIV, leading to the conclusion that the observed enhancement in ionization arises from sources other than plasma interactions. It is suggested that the seemingly anomalous ionization levels can be attributed to firings of thrusters of the attitude control system. In addition, the connection between the shuttle glow phenomenon and the enhanced ionization is considered and found to be circumstantial and not causal, thereby strengthening the argument that the primary source of the shuttle glow is chemical interactions of atmospheric gases with surfaces or with surface-absorbed gases. Keywords;

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