SPACECRAFT-INDUCED PLASMA ENERGIZATION AND ITS ROLE IN FLOW PHENOMENA

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Abstract. Plasma instabilities induced by orbiting vehicles can cause many important phenomena ranging from electron and ion heating and suprathermal electron tail energization, to enhanced ionization and optical emissions. We outline the basic collective processes leading to plasma energization near plasma sheaths and in regions of neutral gas streaming through plasma, and discuss the role of the induced collective effects in producing the optical emission spectra.

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Introduction

As has been emphasized before [Papadopoulos, 1983, 1984], the glow problem is a strongly interdisciplinary one involving aeronomic chemistry, surface physics, and plasma physics. Its understanding requires a coherent experimental, theoretical, and modeling effort, involving all of the above disciplines in a coupled and dynamic fashion. Previous presentations in the workshop emphasized the aeronomical and surface aspects of the interaction [e.g., Kofsky and Barrett, 1985; Dalgarno et al., 1985; Tolk et al., 1985]. It is the purpose of the present paper to outline the plasma physics aspects of the interaction. The correlation of the glow behavior with the modification of the plasma environment in the vicinity of the Orbiter, as observed by the plasma diagnostics package (PDP) [Shawhan and Murphy, 1983], led us [Papadopoulos, 1983] to conjecture that plasma energized by the Orbiter plasma interaction could play a central role in directly producing or mediating the observed glow. This conjecture is strongly supported by the fact that processes relying an surface recombination are unable to account for glow generated far away from the shuttle surface due to thruster or "shuttle surfaces" firing. We review next the observed plasma environment as modified by the Orbiter-ionosphere interaction, followed by a discussion of the induced plasma processes and their role in exciting or influencing the glow spectra.

Implications of the Plasma Environment Near the Orbiter

The plasma environment in the vicinity of the Orbiter under ram conditions is substantially modified over the ambient. Measurements taken by the PDP indicate [Murphy et al., 1983]:

(i) A region near the vehicle which exhibits a density enhancement of at least a factor 2-5 over ambient, reaching values of $10^7 cm^{-3}$;

(ii) A flat suprathermal electron tail above 10 eV, substantially enhanced during thruster operation, with a field-aligned component much flatter than its perpendicular counterpart [see also McMahon et al., 1983];

(iii) An intense electrostatic broadband noise about the lower hybrid frequency;

(iv) Elevated electron temperatures (~6000 K) were observed [Raitt, 1985];

(v) Ion fluxes with up to 30 eV energies, sometimes coincident with single or counterstreaming ion beams, were observed [Stone et al., 1983];

(vi) Large amounts of NO^+, CO_2^+ and H_2O^+, O^+ were observed, being on occasion the dominant ions [Grebowsky et al., 1983; Murad, 1985];

(vii) A gas layer up to 100 times higher than the ambient neutral density was observed.

It is important to notice that the plasma effects were strongly intensified during thruster operations. This intensification correlates very well with the observed glow behavior.

The presence of enhanced low (~1 eV and high ($\geqslant$ 10 eV) energy charged particle fluxes can play a central role in the glow emission and its spectrum because they can:

(i) affect the gas and surface chemistry,

(ii) interact with the ambient neutrals and excite a variety of emissions due to vibration and rotational excitation as well as due to ionization,

(iii) interact directly with the surface and produce emissions in a fashion similar to plasma etching.

Physics of Plasma Energization

In discussing the physics involved in the plasma energization one should first identify the available free energy sources, and then examine the time scale and the form of the energy deposition. The most interesting situations occur when the energy deposition occurs on a collisionless time scale owing to plasma instabilities. We discuss two situations below. The first occurs near the Orbiter surface, and will be associated with surface glow or etching processes. The second occurs over a larger volume, is independent of the presence of a surface, except for creating a dense stream of neutral gas [Rantanen et al., 1985], and will be associated with volume and thruster glow.

Surface Interactions

The phenomena that arise in the neighborhood of bodies moving in a plasma are very complex and their complete solution is beyond the scope of this brief paper. It is sufficient for our purposes to accept that an electric field $\underline{E}(\underline{r})$ arises near the surface due to the different mobility of the electrons and ions. The plasma sheath thus formed slows down the electrons while accelerating the ions to neutralize the charge on the surface [Al'pert, 1983]. The field created due to the difference of the electron and ion densities is of the order of 10-20 Debye lengths (λ_D), which corresponds to 10-20 cm at shuttle altitude. The expected potential is of the order of 2-5 V. For our purposes it is sufficient to accept an electric field E $\approx$ 10 V/m, over a distance of 20 cm. In the presence of a magnetic field $B_o \approx 1/3$ G the electrons will drift with respect to the ions with a velocity $V_D = cE_\perp/B_o$ (Hall current), because $r_e \ll 20\text{cm} \ll r_i$, where r_e, r_i are the electron and ion gyroradii. The value of V_D is given by

$$V_D = 3 \times 10^6 \ E[V/m] \ \text{cm/sec} \ . \qquad (1)$$

Since the ion sound speed $C_s \approx 3\text{-}4 \times 10^5$ cm/sec, $V_D \gg C_s$, resulting in an unstable configuration. The relevant instability is the modified two stream instability [McBride et al., 1972] or the lower hybrid drift instability [Huba and Papadopoulos, 1977]. In the electrostatic limit the dispersion relation in the electron reference frame is given by

$$\frac{\omega_{LH}^2}{(\omega-\underline{k}\cdot\underline{V}_D)^2} + \frac{\omega_{LH}^2}{\omega^2}\left[\frac{k_z^2}{k^2} \quad \frac{M}{m}\right] = 1 \qquad (2)$$

where $\omega_{LH}^2 = \omega_i^2/(1 + \omega_e^2/\Omega_e^2)$ is the lower hybrid frequency, ω_i, ω_e are the ion and electron plasma freuencies, Ω_e is the electron cyclotron frequency, k_z is the wavenumber along the magnetic field and M,m are the ion and electron mass. The lower hybrid electrostatic waves heat electrons and ions with a time scale of ω_{LH}^{-1}, which corresponds to less than 10^{-4} sec for our conditions. The instability has been extensively studied in the laboratory and by computer simulations. The electron heating rate is given by

$$T_e = \frac{1}{n_e}\eta^* j^2 - \left[\frac{\partial T_e}{\partial t}\right]_{mom} - \left[\frac{\partial T_e}{\partial t}\right]_{rot} - \left[\frac{\partial T_e}{\partial t}\right]_{vib} - \left[\frac{\partial T_e}{\partial t}\right]_{ion} \qquad (3)$$

where η^* is the value of the anomalous resistivity, and $(\partial T_e/\partial t)_{mom}$, $(\partial T_e/\partial t)_{rot}$, $(\partial T_e/\partial t)_{vib}$, and $(\partial T_e/\partial t)_{ion}$ are loss rates due to collisions, rotational excitation and deexcitation, vibrational excitation and deexcitation, and impact ionization, respectively. Depending on the rate $\eta^* j^2$ and the abundance of molecular species in the neutral environment a variety of emissions from UV to IR can arise. A quantitative analysis of such a situation is presently under study and will be reported in the future. A proper analysis requires use of the kinetic equation instead of Eq. (3). It is interesting to note that the energy dissipation rate Q is given by

$$Q = \eta^* j^2$$

$$= 10^{-3} \left[\frac{\eta^*}{\eta}\right]\left[\frac{n_e}{10^6}\right]\left(\frac{V_D}{10^7}\right)\left[\frac{N}{10^{11}}\right] [T_e(eV)]^{\frac{1}{2}} \mathrm{erg/cm^3 sec} \quad (4)$$

where η is the resistivity due to the ion-neutral collisions and N is the neutral density. Notice that even for $\eta^* = \eta$ and the canonical problem parameters the energy deposition rate (~10^9 eV/cm^3-sec) is much larger than the 10^8 eV/cm^3-sec associated with the observed orange glow [Kofsky, 1984].

Volume Interactions

These are phenomena associated with interaction of neutral gas streamining through an ambient mangetized plasma. The role of the spacecraft surface is simply to generate a high density neutral gas plume moving with the spacecraft. In this sense the physics of the volume generated glow is similar to the glow due to thruster operation far away from surfaces. An analysis of such interactions can be found in Formisano et al. [1982] and Papadopoulos [1983, 1984]. In contrast to these analyses, we consider here the situation where the conditions for a discharge are not satisfied, owing to lack of sufficient ion reflection. In this case an ion beam moving with the shuttle speed can be generated by charge exchange. This is due to the fact that in a charge-exchange collision each particle retains its original kinetic energy. The density n_b of such a beam will be given by

$$\frac{dn_b}{dt} = \nu_{cx} n_o - \frac{n_b}{\tau} \quad (5)$$

where n_o is the ambient plasma density, ν_{cx} is the charge-exchange collision frequency which we take as $\nu_{cx} \approx 10$ sec^{-1}, and τ is the confinement time of the charge-exchange-generated ions, which move with the shuttle, in the Orbiter vicinity. Since these ions will be lost once their trajectory deviates from straight line, we take $\tau \approx 1/\Omega_i$, i.e., the ion gyrotime. For O^+, $\Omega_i \approx 200$ sec^{-1}. Therefore in steady state

$$\frac{n_b}{n_o} \approx \frac{\nu_{cx}}{\Omega_i} \approx 5 \times 10^{-2} \frac{N}{10^{11}} . \qquad (6)$$

A streaming ion beam with a density ratio $\alpha \equiv n_b/n_o \approx 10\%$ will be formed. In the presence of such a beam the electrons will drift with respect to the ambient ions with velocity U_e by building a polarization field in order to maintain charge neutrality (Figure 1). The dispersion relation of the configuration of Figure 1 is

$$\frac{\alpha\omega^2_{LH}}{(\omega-\underline{k}\cdot\underline{U})^2} + \frac{(1-\alpha)\omega^2_{LH}}{\omega^2} + \frac{\omega^2_{LH}}{(\omega-\underline{k}\cdot\underline{U}_e)^2} \left[\frac{k_z^2}{k^2} \; \frac{M}{m} \right] = 1 . \qquad (7)$$

This system results in the following interactions:

Counterstreaming cross-field ion-ion instability. For $k_z = 0$, flute mode, the third term on the r.h.s. of Eq. (7) disappears and we have the classic counterstreaming ion-ion instability across B_o. The nonlinear behavior of such a system was elucidated as early as 1971 by Papadopoulos et al. [1971]. The ion beam excites hybrid waves which result in collisionless momentum coupling of the ion streams as well as ion heating. The electrons behave adiabatically in the linear stage but are heated by ExB drifts transverse to the flow and B direction. The momentum coupling between the ion streams results in a snowplowing behavior and enhances plasma density in the shuttle vicinity to the point where

$$\frac{n_b}{n_o} = \nu^* \tau_o \quad . \tag{8}$$

In Eq. (8) ν^* is the anomalous momentum coupling rate and τ_o is the ion residence time. From Papadopoulos et al. [1971] and Lampe et al. [1975], $\nu^* = 0.5(n_o/n_b)^{1/3}\omega_{LH}$. The value of τ_o is now different from $\tau \approx 1/\Omega_i$, because the shuttle moving ions are hot. Since we have a finite area $\tau_o = L/V_i$ where V_i is the thermal speed. Taking $V_i \approx U \approx 8$ km/sec; $\tau_o \approx 10^{-3}$ sec. From Eq. (8) we find

$$\frac{n_b}{n_o} = \left[\frac{\omega_{LH}\tau_o}{2^{4/3}} \right]^{3/4} \approx \frac{1}{2} (\omega_{LH}\tau_o)^{3/4}$$

which for $\omega_{LH} \approx 5 \times 10^4$ gives $n_b/n_o \approx 10$. As noted earlier, this is of the order of magnitude density enhancement observed by the PDP.

Beam lower hybrid electron-ion instability. For $(1-\alpha) \ll (k_z^2/k^2)$ M/m the dominant terms in the r.h.s. of Eq. (7) are the first and the third. This is the beam lower hybrid-electron-ion instability discussed by Formisano et al. [1982] and Papadopoulos [1983, 1984]. The instability results in generating field-aligned suprathermal electron tails with density $n_T/\min(n_b,n_o) \approx 0.2$ in the energy range $\approx (1-6) \times \frac{1}{2}MU^2$, i.e., $\approx$ 5-30 eV. These electrons can produce additional ionization as well as contribute to emission from the N_2 first positive system.

Modified two stream instability. For $\omega_{LH} \approx k \cdot U_e$ the first term in Eq. (7) is negligible, and for $\alpha \ll 1$ the dispersion relation is similar to the dispersion given by Eq. (2). This is the modified two stream instability which results in electron heating of the order $T_e \approx \frac{1}{2}MU_e^2 \approx \frac{1}{2}MU^2(U_e/U)^2$. Since from the zero current condition $U_e/U \approx \min(n_b,n_o)/(n_b+n_o) \approx 0.1-0.3$, the electron temperature will be given by $T_e \approx 0.5-1.5$ eV. This again allows for the excitation of various vibrational and rotational emissions.

Summary and Conclusions

We have presented an overview of the types of collective plasma interactions expected to operate in the vicinity of the space shuttle. The model can account for all of the observations of the plasma environment summarized in the section on Implications of the Plasma Environment Near the Orbiter. Quantitative models are currently developed for the optical emissions caused by the plasma energization. It is obvious that the importance of plasma physics vs. aeronomy increases with altitude. The altitude at which this transition occurs is of critical importance and can be found only through active experimentation. At this stage we can summarize the status of the plasma hypothesis as following:

(i) Currents driven by the plasma sheaths in the Orbiter vicinity can increase the plasma temperature sufficiently to bring the molecular constituents to excited states resulting in optical emissions. The expected rate of energy deposition is more than sufficient to account for the observations. Whether and at which altitude radiation due to surface recombination dominates over electron-driven collisional process is an open question.

(ii) Both volume and thruster emissions can be explained by the interaction of neutral gas streaming through the ambient plasma. Surface recombination faces serious difficulties in accounting for these effects. We should note that the time profile of thruster-induced emissions is similar to that of the lower hybrid noise excited by thruster firing.

(iii) The plasma model can easily account for the recently observed 1 KR Lyman alpha emission at 600 km altitude associated with the ram direction of the STP78-1 satellite [Chakrabarti and Sasseen, 1985], as well as for the N_2 first positive observed by ISO [Torr and Torr, 1984].

(iv) A recent active experiment from the space shuttle in which 1 mole of N_2 gas was injected towards the ram direction by the SEPAC team [Obayashi et al. 1984] showed ionization enhancement by a factor of 10 or more in the Orbiter vicinity.

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References

Al'pert, Ya., The Near Earth and Interplanetary Plasma, Vol. 2, Cambridge Univ. Press, 1983.

Chakrabarti, S., and R. Sasseen, these proceedings, 1985.

Dalgarno, A., J. H. Yee, and M. LeCompte, these proceedings, 1985.

Formisano, D., A. Galeev, and R. Sagdeev, Planet. Space Sci., 30, 491, 1982.

Grebowsky, J., M. Paro, H. Taylor, and I. Eberstein, AIAA Shuttle Environment and Operations, Paper #83-2597, p. 52, 1983.

Huba, J., and K. Papadopoulos, Phys. Fluids, 21, 121, 1977 .

Kofsky, I., Radio Science, 19, 578, 1984.

Kofsky, I. and J. Barrett, these proceedings, 1985.

Lampe, M., W. Manheimer, and K. Papadopoulos, NRL Memo Rpt. 3630, 1975.

McBride, J., E. Ott, J. Boris, and J. Orens, Phys. Fluids, 15, 2367, 1972 .

McMahon, W., R. Salter, R. Hills, and D. Delorey, AIAA Shuttle Environment and Operations, Paper #83-2598, p. 52, 1983.

Murad, E., Planet. Space Sci., in press, 1985.

Murphy, G.B., S. D. Shawhan, and J. S. Pickett, AIAA Shuttle Environment and Operations, 1983.

Obayashi, T., et al., Science, 225, 142, 1984.

Papadopoulos, K., et al., Phys. Fluids, 14, 849, 1971.

Papadopoulos, K., in ESA-SP-195, p. 227, 1983.

Papadopoulos, K., Radio Science, 19, 571, 1984.

Raitt, J., Radio Science, in press, 1985.

Rantanen, R., R. Swanson, and D. Torr, these proceedings, 1985.

Shawhan, S., and G. Murphy, Rep. AIAA-83-0253, Am. Inst. of Aero. and Astr., 1983 .

Stone, N.H., U. Samir, K. H. Wright, D.L. Reasoner, and S.D. Shawhan, Geophys. Res. Lett., 10, 1215, 1983.

Tolk, M., R. Albridge, R. Haglund, M. Mendenhall, and J. Tully these proceedings, 1985.

Torr, M., and D. Torr, Science, 225, 169, 1984.

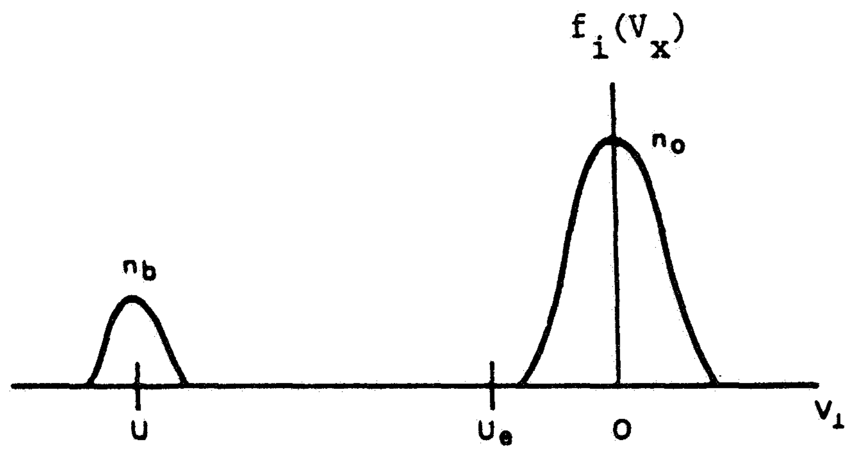

Fig. 1. Ion distribution function in the lab frame, with background ions of density n_o and a charge-exchange-generated beam of density n_b. The electrons (not shown) drift at velocity U_e to maintain zero current.